Properties and applications of quantum dots derived from two-dimensional materials

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ABSTRACT
Quantum dots based on two-dimensional materials (2D-QDs) have received significant attention due to their exceptional physical, chemical, and biological properties. They have shown unprecedented performance and efficiency in many fields including electronics, spintronics, energy, water treatment, sensors, and biological applications. This article provides a critical review on the recent progress of 2D-QDs, their synthesis approaches, categories, properties, and applications. The review introduces various types of 2D-QDs, such as graphene, hBN, silicene, phosphorene, transition metal dichalcogenides, and MXenes that show a wide range of properties applicable for different fields. We describe in detail the electronic, magnetic, optical, catalytic, and biological properties of 2D-QDs and relate them to the suitable applications. Future directions for the research in 2D-QDs are given based on the novel properties provided by the newly discovered 2D materials and their heterostructures.

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1. Introduction

Two-dimensional (2D) materials are ultrathin sheets from atomically thick single layer or few layers. They are considered as innovative materials due to their exceptional properties including excellent mechanical properties [1–3], high thermal and electrical conductivity [4–9], high carrier mobility [10,11], tunable electronic and optical properties [12,13], and high specific surface area [14–16]. Graphene recorded the highest Young’s modulus of 1 TPa and an intrinsic strength of 130 GPa, which are significantly higher than the corresponding values in steel, namely, modulus of ~210 GPa and a strength of ~2600 MPa; thus, graphene is considered to be the strongest material ever measured [1,17]. Other 2D materials show enhanced mechanical properties, such as hBN/MoS₂ with Young’s modulus of 865/270 GPa and intrinsic strength of 70.5/22 GPa [18,19]. In view of their impressive mechanical properties, 2D materials are promising candidates for flexible electronics and electromechanical devices [20]. hBN exhibits an in-plane thermal conductivity as high as 585 W/mK at room temperature that is much higher than its bulk counterpart [21]. This exceptional thermal conductivity, in addition to electrical insulation, makes hBN ideal candidate for next-generation thermal management applications [22,23]. High carrier mobility is another important property crucial for semiconductor devices to minimize power consumption and increase switching speed. Graphene has an extremely high carrier mobility (~2 × 10⁵ cm² V⁻¹ s⁻¹); however, its zero band gap hinders its application in logic gates due to the small current on/off ratio [10]. Fortunately, the family of 2D materials can provide other candidates applicable for this job such as phosphorene (single layer of phosphorus) with mobility up to 2.6 × 10⁴ cm² V⁻¹ s⁻¹ and a moderate band gap of 1.51 eV [24]. Decreasing the thickness of 2D materials significantly improves their optical transparency. Graphene absorbs only ~2.3% of the incident light, which means that graphene is transparent to more than 97% of the incident light. This excellent optical transparency opens the way toward graphene and similar 2D materials for high performance transparent optoelectronic devices [25]. However, for other optoelectronic applications such as photodetectors, graphene and transparent 2D materials are not proper choices due to the low absorption coefficient. Therefore, other 2D materials with high absorption coefficient such as transition metal dichalcogenides (TMDCs), GaS, and 2D heterostructures have been used as efficient photodetectors [26,27]. The optical properties of 2D materials can be precisely controlled by applying external effects such as electric field, strain, and magnetic field [28]. The refractive index of 2D materials can be tuned by applying electric field due to the change of carrier density. This effect involves alternation of the real part of the refractive index and modulation of the phase of the incident light, and therefore can be used in
phase modulators [29], optical switches [30], and coherent optical communication [31]. The large surface area, high surface-to-volume ratio, and the high interactivity of 2D materials widen their application spectrum to include supercapacitors, catalysts, energy storage, and sensors. For example, photoelectrochemical (PEC) biosensing that depends on the electron–hole generation by the light source and the subsequent changes due to the interaction of the target analytes with the recognition molecules is a powerful analytical technique for biomedical applications and environmental monitoring [32]. The photoactive materials of PEC should have high surface area to absorb the maximum amount of incident light, strong absorption capacity, suitable band gap, and enhanced charge separation and transfer to ensure high photo-electricity conversion efficiency. These requirements are achieved in various 2D materials, such as graphitic carbon nitride (g-C$_3$N$_4$), TMDCs, and MXenes [33].

Reducing the lateral size of the 2D materials below 20 nm creates 2D quantum dots (2D-QDs) with discrete energy levels due to the strong quantum confinement [34]. 2D-QDs have almost all the fascinating physical and chemical properties of 2D materials in addition to the capability to precisely tune them and even introduce novel properties using different factors such as size, shape, edge termination, electric field, and chemical functionalization [35–40]. 2D-QDs with quantum confinement in all three dimensions have size-dependent electronic and optical properties, thus a widely tunable photoluminescence has been observed in various 2D-QDs, such as graphene, MoS$_2$, and hBN-QDs [41–43]. They are also promising candidates for polymer reinforcement. For instance, the infusing of graphene QDs (GQDs) into various polymers greatly boosts their mechanical properties with considerable increase in the toughness, tensile strength, and Young’s modulus [44,45]. They have many more characteristics, such as easy functionalization, dissolvability in different solvents, high photostability, and biocompatibility [46–50]. These fascinating properties make 2D-QDs promising applicants in various fields including electronics [51,52], optoelectronics [53,54], sensing [55,56], energy storage [57,58], quantum computation [59,60], and spintronics [61,62]. Here, we provide a comprehensive review of the recent progress of 2D-QDs. Their physical, chemical, and biological properties are introduced and related to different applications. Prospective research on 2D-QDs is given based on the recently discovered 2D materials and their hybrid heterostructures.

2. Synthesis methods

Synthesis of 2D-QDs has been significantly improved in recent years with controllable length, width, and edge type [63,64]. Two main approaches are used for the synthesis of 2D-QDs, namely top-down and bottom-up
approaches. Bottom-up approach shows enhanced capabilities to synthesis 2D-QDs with atomic precision. On the other hand, attached chemical groups, dopants, or defects introduced during the top-down approach are useful for some applications, such as sensors and catalysts; therefore, the choice of the synthetic route is determined by the target application.

2.1. Top-down approach

Top-down methods prepare 2D-QDs via the cleavage of their bulk 2D materials using different approaches such as hydrothermal/solvothermal [65,66], thermal ablation [67], sonication [68], and intercalation [69]. Figure 1 shows the graphical representation of selected approaches used for synthesis of MXenes QDs (MQDs) which in general can be used for the fabrication of other 2D-QDs. As shown in Figure 1(a), the hydrothermal production of MQDs achieved in two steps: (a) the conversion of Ti$_3$AlC$_2$ Max to Ti$_3$C$_2$T$_x$ MXenes by etching using hydrofluoric acid (HF) (b) transformation of Ti$_3$C$_2$T$_x$ MXene into MQDs by hydrothermal treatment at 100 C for 6 h [70]. To avoid the direct use of the hazardous HF in the etching process, Neupane et al. conducted the reaction LiF and HCl at ambient temperature that eventually resulted in HF. The MQDs are then obtained through the chemical solution method at room temperature following a magnetic stirring process for 24 h to etch Al from Ti$_3$AlC$_2$ powder [71]. The intercalation technique (Figure 2(b)) shows high capability to fabricate MQDs with high-yield (60%) and well-defined fluorescent via intercalation of tetramethylammonium hydroxide (TMAOH) between the sheets of Ti$_3$C$_2$T$_x$ at vigorous conditions [72]. The extreme conditions (high temperature, harsh chemicals, etc.) involved in the conventional top-down synthesis of 2D-QDs may lead to a significant degradation of the prepared samples due to oxidization.Recently, H. Alijani, et al. developed a new method to fabricate MQDs based on acoustomicrofluidic approach with negligible degradation [73]. As shown in Figure 1(c), the considerable surface acceleration from the high-frequency electromechanical vibrations produced on piezoelectric substrate nebulizes the layered Ti$_3$C$_2$Tz suspension into single layers and quantum dots.

2.2. Bottom-up approach

Bottom-up synthetic approach is based on the concept of molecular self-assembly in which the atomic or molecular precursors assemble to form the desired 2D-QDs with well-defined structure [74,75]. This approach includes different preparation methods, such as hydrothermal synthesis [76], chemical path deposition [77], and electron beam irradiation [78]. Chen et al. reported a facile bottom-up synthesis of hBN-QDs via hydrothermal
reaction between boric acid and melamine [79], see Figure 2(a). The hydrothermal method is also employed to synthesize MoS$_2$-QDs (Figure 2(b)) using Molybdenum trioxide (MoO3) powder, as molybdenum source, and l-cysteine as sulfur source [80]. Electron beam irradiation method was used to synthesize graphene QDs (GQDs) where 1,3,6-trinitropyrene and hydrazine hydrate were used as molecular precursors to prepare crystalline GQDs as schematically presented in Figure 2(c) [81]. MQDs have also been synthesized using different bottom-up methods [82,83]. For instance, as shown in Figure 2(d), the molybdenum carbide quantum dots (Mo$_2$C-QDs)/carbon
nanosheet composites were synthesized via molten synthesis strategy using Molybdenum acetylacetonate, sucrose, and NaCl as the molecular precursors [84].

3. Categories of 2D-QDs

The family of 2D materials has been expanded to include hundreds of materials with an unprecedentedly wide spectrum of mechanical, electronic, optical, and chemical properties [85–87]. 2D materials can be categorized into single, double, and multi-element 2D materials according to the number of elements they contain [88,89]. The single-elemental 2D materials include planar and buckled 2D materials consisting of only one building atom such as graphene [90], graphyne [91], borophenes [92], silicene [93], stanene [94], phosphorene [95], and antimonene [96]. In this group, 2D materials have planar structure with sp²/sp-sp² hybridization as in
Graphene/graphyne or buckled structure with sp$^2$-sp$^3$/sp$^3$ hybridization as in silicene/antimonene; see Figure 3(a–Figure 3c). The double-element 2D materials contain hBN [97], boron phosphide [98], graphitic carbon nitride (g-C$_6$N$_7$) [99], bismuth nitride [100], TMDs [101], and metal oxides [102].

Boron phosphide and hBN have the same planar structure with strong in-plane sigma bonds like graphene; see Figure 3(e). Graphitic carbon nitride also has a planar structure but with uniformly distributed nanopores where tri-s-triazine (C$_3$N$_3$) rings connect to each other by C-N bonds to form the triangular nanopores structure shown in Figure 3(d). The monolayer TMDCs (such as MoS$_2$ in Figure 3(f)) consist of three sublayers, and the central atomic layer is a transition metal which is sandwiched between two chalcogen layers. The third category is the group of 2D materials containing three or more elements, such as Si$_2$BN [103], MXenes [104], transition metal...
4. Properties

The exceptional physical and chemical properties of 2D-QDs originate from the ultra-high specific surface area, tunable surface chemistry, the quantum size effect, and the superior mechanical properties. Additionally, these advantages can be controlled precisely using different factors such as size, edge type, electric field, chemical functionalization, doping of heteroatoms, and heterostructure formation. Following, we discuss the main properties of 2D-QDs, namely electronic, optical, catalytic, and biological properties.

4.1. Electronic properties

A controllable energy gap is one of the main advantages that quantum dots can add to a material. For instance, graphene with all its unique properties cannot be used in semiconductor devices due to its zero band gap, while GQDs with size-dependent energy gap can solve this problem [35,119]. The energy gap can be increased by decreasing the size of the 2D material as a result of the quantum confinement effect [120]. Figure 4(a) shows a qualitative representation of the increase in the energy gap by decreasing the size of the GQDs [121]. As for the quantitative values of the energy gap, Eda et al.
reported theoretically that the energy gap of a single aromatic ring is as high as ~7 eV and decreases by increasing the number of aromatic rings as presented in Figure 4(b) [122].

The size of GQDs can be controlled experimentally by adjusting the preparation conditions, such as reaction time, temperature, pH level, and reactant concentration [123–126]. In addition to the size effect, the energy gap is also controlled by shape, edge termination, and chemical functionalization. In Table 1, the effects of edge type, shape, and chemical functionalization on the energy gaps of different 2D-QDs are listed based on DFT calculations. GQD with hexagonal shape and armchair termination (AHEX-GQDs, similar to the one shown in Figure 3(e)) has energy gap equals 3.68 eV while for triangular GQD with almost the same number of atoms the energy gap becomes 1.82 eV [127]. The large energy gap in hexagonal-armchair GQD decreases to half its value by functionalizing the edges with...
Table 1. The energy gaps of various 2D-QDs subject to the effects of edge, shape and chemical functionalization.

| Effect of edge and shape | Effect of chemical functionalization |
|--------------------------|-------------------------------------|
| GQDs[127,128] E_g (eV)   | GQDs [127,128] E_g (eV)              |
| AHEx                     | 3.68                                |
| ZHEX                     | 2.89                                |
| ZTRI                     | 1.82                                |
| ATRI                     | 3.27                                |
| SiQDs [62,156] E_g       | SiQDs [62,156] E_g                  |
| AHEX                     | 1.74                                |
| ZHEX                     | 1.38                                |
| ZTRI                     | 1.21                                |
| ATRI                     | 1.56                                |
| PQDs [40] E_g            | PQDs [129] E_g                      |
| AHEx                     | 2.96                                |
| ZHEX                     | 2.77                                |
| ZTRI                     | 3.00                                |
| ATRI                     | 2.82                                |
| hBN-QDs E_g              | hBN-QDs [131] E_g                   |
| shBN                     | 5.59                                |
| AHEX                     | 6.39                                |
| ZHEX                     | 6.51                                |
| ZTRI                     | 4.99                                |

O-atoms or moderately decreases to 3.01 eV by attaching four nitro groups to the edges [128]. De Alwis et al. reported that edge functionalization of rectangular (see Rect in Table 1) PQDs with different chemical groups (e.g. OH, SH, NH2, and OCN) can shift the HOMO and LUMO, which in turn change the energy gap [129].

Some applications require, in addition to a suitable energy gap, other properties such as hardness, interactivity, anticorrosion, thermal stability, and so on. In such cases, mixing the controllable electronic properties with other physical and chemical properties depending on the type of the material will significantly widen the application field of these materials. hBN-QDs have a large insulating energy gap ~6 eV in addition to the high anticorrosion property [130,131], Si2BN-QDs have a narrow semiconducting energy gap of 0.85 eV with high interactivity due to the active pi-electrons from Si atoms [132,133]. Phosphorene quantum dots have energy gap of 3.82 eV in addition to strong linear dichroism due to their buckled structure [134,135]. Quantum dots from TMDCs are characterized by strong spin-orbit coupling in addition to semiconducting properties with energy gaps ranging from 2 to 3.2 eV [136,137].

Moreover, Van der Waals heterostructures formed by vertical or lateral stacking of different 2D materials create materials not only with the combined properties of the constituting materials but also with novel properties [138–140]. Heterostructures based on 2D-QDs have shown exciting electronic properties. For instance, donor-acceptor heterojunction from the same material (PQDs) suitable for solar cells [141] and efficient modulation of electron transfer by forming 0D/2D Van der Waals heterostructure from
GQDs/MoS$_2$ monolayer [142]. PQDs significantly improve the light absorption of MoS$_2$ monolayer in the mixed-dimensional heterostructure from PQDs-MoS$_2$ [143]. Recently, Zhou et al. constructed novel 0D/0D heterostructures from g-C$_3$N$_4$ quantum dots/anatase-TiO$_2$/rutile-TiO$_2$ quantum dots through mixing of TiO$_2$-P25 and g-C$_3$N$_4$ quantum dots followed by thermal treatment [144]. These exceptional type-II/type-II heterojunctions boost the spatial charge separation and transfer of the photo-generated carriers. Additionally, their 0D nature provides them with abundant active sites for efficient photocatalytic reaction.

### 4.2. Magnetic properties

Graphene is characterized by a long spin relaxation time and diffusion length as a result of the small spin-orbit coupling between C-atoms in the planar structure. This property makes graphene a promising candidate in spintronics [145]. However, graphene is a non-magnetic material due to the delocalized distribution of $\pi$-bonds on the periodic lattice [146,147], which is a serious drawback that hinders its applications in spintronic devices [148]. For instance, a spin-valve based on graphene shows a very small magnetoresistance of 10% [149]. Cutting graphene into nanoribbons or quantum dots with zigzag edges is an effective solution to control the magnetic state of graphene, which in turn significantly improves the valves magnetoresistance [150,151]. For example, the nonmagnetic nature of graphene transforms to antiferromagnetic localized states at the zigzag edges of bisanthrene, see Figure 4(c) [152]. This is the smallest polycyclic aromatic hydrocarbon representing spin polarized nanoribbons from graphene [152]. Additionally, triangular QDs from graphene, silicene, and/or any 2D material have frustrated edge atoms (Figure 4(e)) with unpaired electrons on the zigzag edges. These electrons cannot form delocalized bonds with neighbor atoms and instead form half-filled molecular orbitals that create a ferromagnetic spin ordering [153–156]. It is important to note that not all bipartite systems with zigzag termination have magnetic properties. For instance, hBN is a bipartite lattice; however, its electrons are hybridized to form only three sigma bonds with no unpaired $p_z$-orbital electrons unlike graphene or silicene [157,158]. The net spin (S) due to the unpaired electrons can be obtained from Lieb’s theorem of bipartite lattices [159] using the following simple equation: $S = (N_A - N_B)/2$, where $N_A$ and $N_B$ represent the number of atoms of A and B sub-lattices, respectively. Using this equation, the net spin of triangular graphene or silicene with 5-edge hexagons equals 2 with higher spin-up density on the edge atoms; see Figure 4(f). Ahin et al. [153] indicated that double hydrogenation of the edge atoms of triangular-zigzag GQDs removes the spin states at the edges due to passivation of all edge electrons and induces frustrated surface atoms with
half-filled molecular orbital and a net spin increased to $S = 4$ (Figure 4(e)). On the other hand, Abdelsalam et al. reported that surface hydrogenation of triangular-zigzag SiQDs significantly increase the net spin to $S = 7.5$ with a perfect spin density difference distributing on edge atoms as shown in Figure 4(h) [62]. Despite the multiple difficulties of synthesizing these materials due to their high chemical reactivity, however, the recent advance in the on-surface synthetic approach allows for the fabrication of triangular-zigzag GQDs with permanent high-spin [160–162]. Recently, Liu et al. showed that triangular-zigzag GQDs can be linked together using various linkages (e.g. small GQDs, magnetic metal atoms, and molecules) to form 2D magnetic semiconductors with enhanced Curie temperature up to 472 K [163].

The rich family of 2D materials also offers intrinsic 2D magnetic materials (regardless of the shape, edge termination, or any external effects) with magnetism originating from the half-field d-orbitals of the transition metal. Such as the observed ferromagnetism in Fe$_3$GeTe$_2$ [164] and chromium triiodide (CrI$_3$) [165] at low temperature, while monolayer vanadium selenide (VSe$_2$) shows strong ferromagnetic ordering at room temperature and higher [166]. Figure 4(i) shows the graphical representation of the spin orientation in the 2D-CrI$_3$. In addition to ferromagnetism, 2D magnetic materials include insulating antiferromagnets such as MnPS$_3$ [167] and materials with large magnetic anisotropy such as $\alpha$-RuCl$_3$ [168]. These 2D magnetic layered materials represent an ideal platform to study and control magnetism in 2D limits [169–172]. Quantum dots from these 2D magnets have not been investigated yet, according to the best of our knowledge, due to the very recent discovery of these 2D materials. Regarding the conventional QDs or the magnetic nanoparticles, it is known that Curie temperature drastically decreases by decreasing the size of the nanoparticles [173, 174]. Also, decreasing the thickness of 2D magnetic materials decreases the Curie temperature [175]. Thus, decreasing the size of 2D magnets to the quantum regime may decrease the Curie temperature in the resultant 2D-QDs. This may not occur and the Curie temperature increases similarly to the anomalous increase in Curie Temperature by decreasing the thickness of the 2D metallic 1 T-CrTe [176]. Therefore, prospective works on magnetic 2D-QDs are crucial for both fundamental understanding of 2D magnets and also for building efficient 2D spintronics.

4.3. Optical properties

The optical properties of 2D-QDs are tunable and cover a broadband range of wavelengths starting from ultraviolet to infrared [177–182] due to the size-dependent quantum confinement [117, 183], edge type [184, 185], chemical functionalization [186, 187], and doping [188, 189]. According to the
quantum confinement effect, the energy gap of a quantum system is approximately proportional to $1/L$ where $L$ is the size of the quantum dot. Then, changing the size of QDs changes the energy gap and consequently the optical properties. It has been reported that the absorption and photoluminace spectra of GQDs strongly depend on the size where the absorption and emission spectra are blue shifted by decreasing the size of the GQDs [190,191]. Regarding the edge type, the photoluminance (PL) of GQDs shows peculiar behavior when the average size becomes higher than 17 nm where the energy of the PL peak increases by increasing the average size [190]. This behavior, which does not follow the quantum confinement effect, arises due to the change in the edge type from a mixed zigzag and armchair terminated edges to edges with mostly armchair terminations. The effect of edge type on the optical properties of SiQDs was also investigated theoretically using tight binding model [192]. The calculations show that triangular SiQDs with zigzag termination have a reach and widely controllable infrared absorption peak originates due to transitions from or to edge states. This absorption peak disappears in triangular SiQDs with armchair termination due to the disappearance of the low energy edge states. With respect to chemical modification, Ding et al. managed to modulate the photoluminescence of hBN-QDs to include full-color emission (420–610 nm) by attaching amino ligands to the edges [185]. As shown

Figure 5. (a) Illumination photographs of chemically functionalized hBN-QDs under 360 UV-irradiation. (b, c) Emission and absorption spectra of hBN-QDs. (d) Absorption spectra of MQDs with different concentrations. (e) Normalized absorbance intensity divided by the characteristic length of the cell ($A/L$) for varied MQDs concentrations. (f) MQDs photothermal heating curves at different power densities. The plots (a-c) and (d-f) are reproduced with permission from [185] and [199], respectively.
in Figure 5(a–c) a full-color photoluminescence emission and UV-Vis spectra can be achieved in hBN-QDs by attaching specific amine ligands in different solvents. Namely, blue hBN-QDs (B-QD) is obtained by attaching urea to N-methylpyrrolidone, green hBN-QDs (G-QD) by attaching p-phenylenediamine to sulfuric acid. Green-yellow, yellow, and red hBN-QDs (GY-, Y-, and R-QD) are obtained by passivation with thiourea ligand in acetone, p-phenylenediamine in dimethylformamide, and p-phenylenediamine in ethanol, respectively. Therefore, good thermal dissipation, high transparency, and full-color emission make hBN-QDs promising applicants for thermostable, transparent, and flexible displays.

In addition to these effects, plasmonic effect of metallic QDs can significantly enhance the absorption of light [193]. In plasmonic effect, conduction electrons of the metallic QDs oscillate collectively when their frequency matches that of the incident electromagnetic wave causing strong absorption of light. Plasmons were observed in various 2D-QDs, such as GQDs [194], MoS2-QDs [195], and MQDs [196]. Neupane, et al. reported highly enhanced photoluminescence in MQDs-WS2 heterojunction due to the plasmonic behavior of MQDs and the suspension state of WS2[196]. Another interesting property found in MQDs is their high capability to absorb light and convert it to different forms of energy [197,198]. For instance, Yu et al. reported the synthesis of biocompatible (fluorine-free) Ti3C2-QDs with not only strong absorption in the near-infrared region and mass extinction coefficient equal to 52.8 Lg−1 cm−1, but also high photothermal conversion efficiency of up to 52.2% [199]. The UV-Vis-IR spectra at different concentrations of MQDs in Figure 5(d) show strong and broadband absorption in the near-IR region. In addition to the quantum confinement effect, this enhanced absorption is suggested to be a result of the localized surface plasmon resonance improved by the Al oxoanions (Al(OH)4−) on the surface formed by the fluorine-free synthetic approach [199,200]. The calculated value of mass extinction coefficient, a tool to evaluate the light absorption efficiency, shown in Figure 5(e) is very high compared to other photothermal based on 2D materials [201–203]. In addition to the strong absorption capability, MQDs show promising photothermal conversion efficiency, where the temperature of a solution of 10 ppm MQDs solution increases by 14.1°C after laser irradiation for 5 min as seen in Figure 5(f), while irradiating pure water at the same condition produces negligible temperature increase.

4.4. Catalytic properties

The abundant active sites, in addition to the tunable physical properties previously discussed, make 2D-QDs promising candidates for efficient catalysts [58,204,205]. Reducing the size of 2D sheets to QDs strongly
enhances the effect of edges where the density of states is strongly enhanced at the zigzag edges that form high-density active sites [206–209]. The unsaturated atoms formed at the edges of the nanodots are highly interactive. They can easily interact with surrounding atoms or molecules, such as the strong electrocatalysis observed at the edges of WS$_2$- and VS$_2$-QDs [210–212]. The high surface area and defects also increase the active sites at the surface [213,214]. Moreover, doping, chemical functionalization, and heterostructure formation strongly boost the catalytic performance. For example, N-doped GQDs have superior electrocatalytic properties compared to their N-free counterparts [215]. N-atoms are widely used in doping carbon-materials due to their comparable atomic size to C-atoms with significantly enhanced electronic and catalytic properties [216,217]. The electronegativity of the substitutional doped N-atom is higher than the neighbor C-atoms leading to electron transfer from C to N. Thus, the positively charged C-atoms will be the active site with high density of states around the Fermi level [218]. This charge redistribution significantly improves the catalytic performance of graphene from being poor electrocatalyst with low electron transfer and poor electrochemical activity [219,220] to efficient electrocatalyst after doping [221,222]. Additionally, hBN-QDs show superior catalytic properties toward hydrogen evolution reaction (HER), with free energy change equal to 0.11 eV [131] comparable to 0.09 eV for the benchmarking platinum catalyst [223]. However, pristine hBN-QDs show low overall catalytic performance due to their wide insulating energy gap that decreases the electron transport and eventually affects the Tafel slope. This problem can be solved by doping or by attaching chemical groups to tailor the electronic properties and improve the electron transport [131,224]. Based on this idea, doping GQDs with heteroatoms (nitrogen, boron, sulfur, and phosphorus) can help construct highly efficient C-based metal-free catalysts [225,226]. With respect to TMDCs, doping enhances the electrocatalytic HER by decreasing the change in the free energy and introducing more active sites [227,228].

In Figure 6, we present the catalytic performance of different 2D materials toward HER. It is observed from Figure 6(a) that doping decreases the HER free energy with the highest decrease in the N-S codoped graphene, $\Delta G_{H^+} = 0.23$ eV, and thus the best HER catalytic performance [229]. The polarization curves present an important role of doping in decreasing the value of the HER overpotential of graphene toward that of MoS$_2$. The potential in the current density-potentials curves (polarization curves) represents not only the thermodynamic potential for HER plus the overpotential but also ohmic potential originated from the internal resistance of the system [233,234]. Interestingly, combining both the N-S doping and the defects in porous graphene introduces an additional improvement to the HER with $\Delta G_{H^+} = 0.12$ eV [235] which is lower than $\Delta G_{H^+} = 0.15$ eV for the
metal-based MoS\(_2\) catalysts. Another interesting idea that may introduce further decrease in the overpotential is the addition of the effects of quantum confinement and shape that appear in QDs to the effects of defects and doping. The volcano plot and the polarization curves in Figure 6(c,d) shows that metal-doped MoS\(_2\) sheets are exceptional HER electrocatalyst with extremely low overpotential down to 0.06 eV in Pt-doped MoS\(_2\) [230]. Ding et al. reported that the role of Pt-dopants is to boost the activity of the neighbor S-atoms, where they found that the \(\Delta G^*_{\text{H}^+} = 0.06\) eV on the in-plane S-atoms, while \(\Delta G^*_{\text{H}^+} = 0.1\) eV on edge S-atoms [230]. Since there are few studies on HER using 2D-QDs, we represent only in Figure 6(e) the effect of reducing size on the HER catalytic performance of N-doped MoS\(_2\). It is seen from the plot that reducing the size significantly enhances the catalytic properties, namely by lowering the overpotential from \(\Delta G^*_{\text{H}^+} = 0.095\) eV in N-MoS\(_2\) nanosheets to \(\Delta G^*_{\text{H}^+} = 0.082\) eV in N-MoS\(_2\) QDs [231]. Moreover, chemically modified MXenes (e.g. Ti\(_2\)C and V\(_2\)C) have remarkable catalytic properties; Gao et al. show that oxygen-atoms at the surface provide active sites for HER with exceptional overpotential equals −0.04 eV [232]. Therefore, chemical modification and decreasing the size of 2D sheets to the quantum regime may lead to the construction of efficient catalysis that can replace the highly expensive Pt-based catalysts.

Figure 6. (a) HER free energy diagram and (b) polarization curves of graphene before and after doping; reproduced with permission from [229]. (c) The Volcano plot of metal-doped MoS\(_2\) and in (d) the corresponding polarization curves for selected dopants are shown, with permission from [230]. (e) Comparison of the polarization curves of N-doped MoS\(_2\) quantum dots and nanosheets, reproduced with permission from [231]. (f) DFT calculations of the Volcano plot of various 2D MXene with and without termination by O-atoms reproduced with permission from [232].
4.5. Biological properties

Due to its high biocompatibility, easy chemical functionalization, good solubility, degradability, small size, and the exceptional physicochemical properties, 2D-QDs are excellent candidates for biological applications. Tabish et al. reported excellent biological properties of GQDs such as exceptional photoluminance, high water solubility, excellent corrosion resistance, high photo/pH-stability, and good in vitro and in vivo biocompatibility [236]. Other 2D-QDs such as hBN-, g-C3N4-, antimonene-, TMDC-, M-QDs exhibit remarkable biological properties [237–241]. An important biological application is drug delivery, where we show its mechanism using GQDs in Figure 7. In that respect, chemical functionalization, on the surface and/or the edges, is crucial to obtain an efficient 2D drug delivery system [242]. Chemical groups or elements attached to the GQDs form the active sites through which different biomolecules, e.g. drugs and targeting legends, can be loaded onto the GQDs. Biomolecules can also be loaded on the surface by electrostatic bonding, π-π interactions, hydrogen bonding, which in addition to the active groups on the surface make GQDs ideal drug carriers. The active chemical groups on the surface can also improve the quantum yield and the photoluminescence. For instance, Qian et al. showed that functionalized GQDs have better bioimaging characteristics compared to pristine-graphene due to their high quantum yield [243]. Iannazzo et al. indicated that GQDs could then be used as an efficient drug delivery system capable of delivering the therapeutic drug to cancer

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Mechanism of drug delivery using GQDs, reproduced with permission from [242].
cells in selective way [244]. Namely, the drug (e.g. doxorubicin) is adsorbed on the surface of GQDs through the π-π interactions and the tumor-targeting module (e.g. biotin that is able to recognize cancer biotin receptors) is covalently bound to the carboxylic group on the edge of GQDs. Additionally, the exceptional photoluminescence of functionalized GQDs allows for the precise tracing of the drug release. Alongside GQDs, MoS$_2$-QDs have demonstrated great potential in drug delivery due to their excellent biocompatibility, tunable photoluminescence, and high cellular uptake [245, 246]. Liu et al. demonstrated that MoS$_2$ nanosheets functionalized with polyethylene glycol are promising multifunctional drug delivery systems due to their high capacity for drug loading and the strong near-infrared absorbance [247].

5. Applications

The unique physical, chemical, and biological properties of 2D-QDs make them attractive for a wide range of applications. In this work, we will discuss the potential applications of 2D-QDs in the following fields, electronics/optoelectronics, spintronics, energy, water treatment, sensors, and biological applications.

5.1. Electronics/optoelectronics

2D-QDs with tunable electronic properties found their applications in various electronic devices, such as transistors, light-emitting diodes (LEDs), and memory devices. 2D transistors with ultrahigh mobility, exceptional flexibility, and high environmental stability are expected to form the future of high-speed flexible electronics that could outperform organic semiconductors [248]. Chen et al. reported the best-performing 2D-MoS$_2$ transistors to date with an on/off ratio higher than 10$^7$, an intrinsic gain ~30, an intrinsic cut-off frequency of 42 GHz in addition to a maximum power gain of 50 GHz. As shown in Figure 8, graphene single-electron transistor (SET) can be achieved by connecting GQDs to source and drain electrodes through two graphene constrictions with four side gates that tune the electronic properties [35, 249, 250]. Therefore, 2D-QDs provide stable and conductive SET with one-by-one electron transfer at the molecular scale [251].

Phototransistors are another interesting application of 2D materials and their hybrid systems due to high sensitivity, suitable energy gap, and high carrier mobility [252-254]. Seo et al. reported an ultrasensitive avalanche and broadband light-detection phototransistors based on MoS$_2$ monolayer
2D-QDs with tunable emission spectra, improved quantum yield, and long lifetime are vital for the development of light-emitting diodes with enhanced efficiency, brightness, compactness, and energy saving \([256–262]\).

In the field of data storage 2D-QDs show good stability, multilevel data storage, high on/off ratio such as PQDs \([263,264]\) and TMDCs-QDs \([265,266]\). Flash memory is an example of memory devices, in which data are stored as electric charges in discrete charge traps such as quantum dots. Joo et al. have prepared a charge-trap flash memory based on GQDs, see Figure 9, with controllable memory properties depending on the size of GQDs \([267]\). A schematic representation of the memory capacitor is shown in Figure 9(a) such that GQDs are between the tunnel and the control SiO\(_2\) layers, located on a p-type Si wafer. The write/erase processes were performed by applying voltage pulses on the Al electrode. In the writing process, under a positive voltage applied to the control gate, electrons tunnel from the substrate (Si) through the tunnel barrier (SiO\(_2\)) to the conduction band of GQD and are trapped in its continuum states, see the energy band diagram in Figure 9(c) for the writing process. Applying a negative bias, during the erase process, causes electrons tunneling from GQDs to the Si-conduction band through the SiO\(_2\) tunnel barrier.

5.2. Spintronics

The interesting magnetic properties of 2D-QDs open the way toward their applications in various semiconductor spin-based applications, including, spin transistors, spin logic switches, spin valves, magnetic tunnel junctions, magnetic field sensors, valleytronic and quantum information technology.
These spin-based devices have higher performance, lower power consumption, and higher stability than traditional electronics based only on electronic charges. 2D materials with permanent spin such as Rashba spin-orbit coupling in silicene can solve some problems of the spin field-effect transistors with injected spin such as mismatch and spin lifetime [270]. Efficient spin-field switch devices can be achieved in graphene-MoS₂ heterostructure with undisturbed spin transport over a long distance due to the weak spin-orbit coupling of graphene and at the same time precise control over the electron spin by the strong spin-orbit coupling of MoS₂ [271].

Magnetic tunnel junction (MTJ) is a device consisting of ferromagnetic layers separated by a very thin insulating layer. The resistance of this device depends on the magnetization direction in ferromagnetic layers that can be controlled by an external magnetic field. In the parallel orientation, the resistance is lowest while in the antiparallel orientation the resistance is highest. MTJ is a basic principle on which many important applications work, such as magnetic field sensors, magnetoresistive random access memory (MRAM), and read heads for hard drives. 2D materials, especially those with intrinsic ferromagnetism and high-spin polarization, bring many opportunities for the future-generation of MTJ [272].

TMDCs have strong spin-valley coupling due to inversion symmetry breaking and spin-orbit coupling [273]. The strength of the coupling can be further increased by decreasing the size. For instance, the spin-valley coupling of 400 meV in WS₂ monolayer can be increased to 570 meV in WS₂-QDs (size ~8–15 nm) or even to 821 meV in smaller WS₂-QDs (size ~1.8–3.8 nm) [274,275]. Therefore, WS₂-QDs with giant spin-valley coupling due to quantum confinement are excellent candidates for valleytronics. Regarding quantum information processing, the spin of an electron in QDs can be used to form the two-level system of a qubi, and then an array of such quantum dots with controllable coupling can work as spin-based quantum computers [276,277]. The tunable properties provided by 2D-
QDs such as graphene and TMDCs quantum dots motivate many researchers to investigate their use as spin qubits with long coherence times and fast operation times [278–281].

5.3. Energy

The energy applications of 2D-QDs can be divided into two categories, (a) energy storage and (b) energy conversion.

5.3.1. Energy storage

Supercapacitors are examples of widely studied energy storage devices due to their high power density, ultrafast charging/discharging rate, long cycle lifetime, and flexibility [282–284]. The ultimate surface area, interactive edge states, defects, and doping of 2D-QDs can help construct highly efficient supercapacitors [285]. For instance, GQDs doped with nitrogen and MoS$_2$-QDs present outstanding electrochemical activity as negative and positive electrodes, respectively. Namely, the prepared N-GQDs/MoS$_2$-QDs supercapacitor exhibits high operating voltage of 1.5 V, extremely fast frequency response, high energy density of 0.55 mWh cm$^{-3}$, and long-term cycling stability [286]. Moreover, supercapacitors from Ti$_3$C$_2$T$_x$/Ti$_3$C$_2$T$_x$ QDs/reduced graphene oxide have high capacitance and excellent flexibility. The constructed device shows a volumetric capacitance of 53.1 F cm$^{-3}$ and good cycle stability of 96.6% after 5000 cycles. Additionally, it has an operating voltage of up to 1.5 V and a volumetric energy density of 16.6 mWh cm$^{-3}$ [287]. Another energy storage example is batteries with higher energy storage compared to supercapacitors, but they can take hours to be recharged. This difference is mainly due to the operating mechanisms in both devices, where batteries employ chemical reactions to create and store electrical energy, while supercapacitors store electrical energy using the mechanism of electric double-layer effect. In recent years, tremendous efforts in the field of energy storage have been dedicated to explore new materials that can combine the high energy density of batteries and short charging time of supercapacitors [288]. 2D materials have the potential to improve the power and rate capabilities of supercapacitors and at the same time enhance the energy density up to that of batteries [289–291]. Pan et al. have fabricated a 3D doped porous-graphene hydrogel as electrodes for ultrahigh energy density supercapacitors. The designed supercapacitor with a commercial-level graphene mass loading (150 µm, ~10 mg cm$^{-2}$) can deliver an ultrahigh energy density of 38.5 Wh kg$^{-1}$ that is comparable to that of lead-acid batteries (35–40 Wh kg$^{-1}$) but with an ultrahigh power density of 83 kW kg$^{-1}$ and a long cycle life [292].
5.3.2. **Energy conversion**

Photovoltaic cells, by which sunlight is converted to electricity, are an important application of 2D-QDs in the field of energy conversion that has grasped significant attention in recent years [65,293–296]. Due to the wide range of light absorption, high quantum yield, generation of multiple exactions, and ultrafast carrier transfer, 2D materials are expected to construct the next-generation solar cells [297–301]. Graphene with its high transparency and conductivity can be used as electrodes (anode or cathode) in the solar cells. In contrast, TMDCs with direct band gap and strong light–matter interaction can be used as the active semiconductor materials. 2D-QDs can be used in organic or perovskite solar cells as electrodes, electron/ hole extraction, and interfacial layers [302]. The working mechanism of organic or heterojunction-based solar cells is shown in Figure 10(a). The absorbed sunlight photon generates electron–hole pairs (excitons) in the donor material. The excitons with moderate binding energy are then dissociated into free electrons and holes at the interface of the donor-acceptor. Finally, the electrons and holes move through the electron transport layer (ETL) and hole transport layer (HTL), respectively, toward the electrodes and operate at the external circuit. The perovskite solar cell shown in Figure 10(b) has a slightly different operating principle, where the perovskite active

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**Figure 10.** Band alignment of different layers in organic (a) and perovskite solar cells (b) presenting their working principles, reproduced with permission from ref [301]. Heterojunction solar cell based on 2D-QDs (c), its band diagram (d), and the resultant PCE (e), reproduced with permission from [313].
material absorbs the sunlight to generate excitons. The dissociation of electrons and holes occurs at the interface between the perovskite material and the charge transporting layers, as seen in Figure 10(b).

Perovskite solar cells are characterized by a low exciton binding energy (~0.05 eV), which facilitates exciton dissociation with minimal energy loss associated with the dissociation and migration [303]. They also have a suitable band gap and absorption coefficient higher than 10^4 cm^{-1} in the visible region, making them superior to all other solar cells [304].

We now turn to the integration of 2D-QDs into the solar cell devices and their capabilities to boost the power conversion efficiency (PCE). Chen et al. found that PQDs with high hole mobility over 100 cm²/(V.s) integrated at the anode side of hybrid perovskite solar cells improve the performance (PCE increases from 14.10% to 16.69%) by enhancing the hole-extraction and suppression of recombination at the anode [305]. The performance of bulk heterojunction solar cells can be improved by adding GQDs, where the functional groups on the surface of GQDs enhance the electron extraction and light absorption [306]. TMDCs-QDs have been used as ETL, interfacial layer, and HTL in organic solar cells [307,308]. For instance, the performance of inorganic solar cells is boosted by manipulating the size of MoS₂-QDs as an HTL [309]. All-2D heterojunction solar cells have also been investigated which are vertically/laterally aligned 2D materials with type-II band alignment suitable for solar cells. Different 2D-based heterojunction solar cells were constructed, such as Phosphorene/MoS₂ [310], MoS₂/WSe₂ [311], and Te/WTe₂ [312]. Heterojunction solar cells based on 2D-QDs have also been reported with superior PCE [295,313]. We recently designed a heterojunction solar cell from silicene and graphene QDs, see Figure 10(c-e), and proved that the shape, size, and edge termination are crucial factors for boosting the PCE up to 23.34% [313].

Water splitting is a chemical process in which water decomposes into hydrogen and oxygen. In this process, 2D-QDs can be used as photocatalysts or electrocatalysts that enhance the conversion of solar energy or electrical energy into chemical energy (hydrogen). Water splitting is divided into two main reactions: oxygen evolution reaction (OER) at the anode and hydrogen evolution reaction (HER) at the cathode as given by the following equations.

\[ \text{H}_2\text{O} + * \rightarrow 2\text{H}^+ + 1/2\text{O}_2 + 2e \]  \hspace{1cm} (1)

\[ 2\text{H}^+ + 2e^- + * \rightarrow \text{H}_2 + * \]  \hspace{1cm} (2)

Where * represents the catalyst. The significant enhancement of HER using 2D-QDs as catalysts has been previously discussed in section (4.4), thus we will discuss only OER here. OER is very important for renewable energy
conversion and storage devices, such as fuel cells and researchable metal-air batteries [314–316]. Efficient electrocatalysts for OER can be characterized by low overpotential, low Tafel slope, high stability, and cost-effective. So far, precious-metal oxides, e.g., RuO$_2$ and IrO$_2$, have been benchmarked as OER electrocatalysts; however, they have limited stability and high cost. Therefore, it is highly important to search for OER electrocatalysts based on new materials that are efficient, low cost and stable. 2D-QDs with abundant active sites, defect-rich, highly exposed surface area, and functionalized surface showed enhanced OER activity such as functionalized PQDs [39], MoS$_2$-QDs [317], GQDs [318], MQDs [319]. Prasannachandran et al. reported that chemically functionalized PQDs are efficient OER electrocatalysts with an overpotential of 1.66 V, a low Tafel slope of 48 mV dec$^{-1}$, and excellent stability [39]. The reach crystal defects in T$_3$C$_2$ MQDs significantly lower the OER overpotential to 0.37 V [319]. Moreover, PQDs/MXenes heterostructures showed exceptional bifunctional electrocatalytic performance for both OER and HER. Namely, an overpotential of 360 mV and a Tafel slope of 64.3 mV dec$^{-1}$ have been achieved for OER, for HER, the overpotential equals 190 mV and the Tafel slope equals 83 mV dec$^{-1}$[320].

5.4. Water purification

2D membranes capture a great attention due to their potential applications in water purification [321–325]. 2D materials open the way toward new approaches for the improvement of membranes that bulk materials cannot achieve, for examples, controllable pore size, non-corrosive property, high mechanical strength, tunable surface chemistry, ultrathin structure, high adsorption, and high permeation rate [326–328]. We showed that graphene, hexagonal boron nitride, and Si$_2$BN QDs are capable of removing various toxic metals from wastewater with high adsorption energy and negligible deformation [131,133,329]. Regarding the controllable pore size, Jacobse et al. demonstrated a novel bottom-up approach to fabricate nanoporous graphene with precise nanopores topologies using dihalide monomers as seen in Figure 11(a) [330]. The fabrication process consists of three steps: (a) aromatic dihalide monomers are covalently coupled to form polymer chain, (b) aromatization of polymer chain by dehydrogenation of the cyclic compounds to form 2D nanoribbons, and (c) the final step is the lateral binding of nanoribbons through selective dehydrogenative coupling. Based on this idea, the pore size can have additional control by using different monomers such as Hexakis(4-bromophenyl)benzene (HBPB, Figure 11(b)) to synthesize porous graphene, which looks like laterally connected hexagonal GQDS [331]. Layer stacking can also enhance the adsorption and sieving properties of 2D membranes. As shown in Figure 11(c), in monolayer membranes some metal ions can sieve through the nanopores; however, by formation of
multilayer 2D membranes, these ions are blocked between the layers [332]. Therefore, 2D membranes are bifunctional materials for wastewater treatment due to high adsorption energy and surface area, as well as for seawater desalination due to their ability to permute/block water/salt molecules.

5.5. Sensors

The high sensitivity, selectivity, tunable photoluminescence, and non-toxicity of 2D-QDs show great potential for both chemosensors and biosensors [333–336]. Chemosensors are sensory receptors that can interact with the analyte and produce detectable signals [337]. Biosensors have the same working principle with the only difference of attaching biological recognition receptors to the nanomaterials such as antibodies, and enzymes, DNA etc [338]. Emissive chemosensors based on 2D-QDs with noticeable change
in the PL, because of interaction with the analyte, are used as efficient fluorescent probes for various analytes including metal ions [339–344], gases [345–349], and organic molecules [350–354]. Electrochemical sensors from 2D-QDs have also been investigated [355–358]. With respect to biosensors, the 2D-QDs need to be modified with recognition receptors, GQDs modified with antibodies form immunosensors with high sensitivity and specificity toward Yersinia enterocolitica [359]. Ge et al. constructed a highly sensitive fluorescence biosensor for microRNA detection by coupling MoS$_2$-QDs with nicking-enhanced rolling circle amplification [360]. Moreover, a naked eye fluorescence probe for uric acid has been developed based on the fluorescence quenching of glutathione functionalized Ti$_3$C$_2$ QDs and uricase/HRP enzymes [361].

### 5.6. Biological applications

In addition to drug delivery and biosensing discussed in sections 4.5 and 5.5, respectively, 2D-QDs show promising properties for other biological applications including bioimaging and phototherapy [362]. Photoluminescent 2D-QDs such as GQDs [363, 364], g-C$_3$N$_4$-QDs [365], PQDs [366], MoS$_2$-QDs [367], and MQDs [368] have drawn significant interest in the field of bioimaging due to their intriguing optical emission properties, stability, and biocompatibility. Fluorescence imaging, which is a non-invasive tool that visualizes biological processes using the photons emitted from a fluorescence probe, provides a highly versatile platform for molecular imaging [369]. Recently, M. Shi et al. reported a bottom-up synthesis of MoS$_2$-QDs with excellent fluorescence properties and biocompatibility that enabled fluorescence imaging of SW480 tumor cells in vitro and in vivo [370]. Other types of bioimaging based on 2D-QDs such as magnetic resonance, computed tomography, and photoacoustic imaging have also been investigated [203].

Phototherapy based on 2D-QDs such as GQDs [371], g-C3N4 [372], MoS$_2$ [373], and MQDs [374] demonstrated high capability to treat various diseases [375]. The phototherapy process starts by directing the phototherapeutic agent to the diseased part and then irradiated with light. In photodynamic therapy, the absorbed light generates reactive oxygen species that induces irreversible damage to tumor cells [376]. The second type of phototherapy is the photothermal therapy in which the absorbed infrared light by the agent is converted to heat that causes cells ablations as schematically shown in Figure 12 for Mo$_2$C-QDs as the photothermal agent [377].
Motivated by their outstanding properties, 2D-QDs are expected to form a cornerstone in building future nanodevices. Significant advances in experimental techniques facilitate the synthesis of various 2D-QDs including graphene, silicene, TMDCs, MXenes, etc. with enhanced and tunable physical and chemical properties. However, atomic precision synthesis of 2D-QDs with definite shape, edge termination, layer number, and nanopores has been achieved only in GQDs. Therefore, future work should focus on atomic precision synthesis of different 2D-QDs such as triangular shapes with zigzag termination that show exceptional magnetic and catalytic properties. There are a huge number of 2D materials, either theoretically predicted or synthesized. Since 2D-QDs have improved properties, such as electronic energy gap, photoluminescence, electron density around Fermi level and active edge states, with respect to their bulk 2D counterpart, it is highly important to investigate QDs derived from them. For instance, the recently fabricated 2D magnets (e.g. CrI$_3$ and VS$_2$) are expected to show many interesting properties in the quantum regime. Heteroatom doping of 2D-QDs, which is an important tool to control the physical and chemical properties of a material, is still in its infancy. Systematic investigations on the effect of doping with single atoms (such as S, N, P, or metal-atoms) or co-doping (N-S, N-P, N-Pt, etc.) on 2D-QDs based on TMDCs, MXenes, etc. are required because it can open up the way for applications in catalysis and energy. Hybrid heterostructures based on 2D-QDs, e.g. 0D/2D (GQDs/2D-metals or metal-QDs/WS2) and 0D/0D (GQDs/VSe$_2$-QDs or PQDs/
MXenes), worth more investigations due to their capability to combine the privileges of different materials in one heterostructure.

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