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Revolutionization on display-technology based on carbon quantum dots and the impact after heteroatom doping: Nanotechnology-assisted next generation lightning

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Abstract- This article focused on the exploration of innovative 'quantum dot technology' based on highly luminescent carbon quantum dots (CQDs) materials for display, solar cell, sensing and biomedical applications. Using hetero-atom doping on CQDs with N, O, P, S etc., the 'display technology' has been revolutionized, leading to improved image quality, energy efficiency, customizable color emission and enhanced brightness for high-quality visuals, wider color gamut and more vivid, lifelike images. This article also attentive on how the cost-effective and eco-friendly CQDs can revolutionized 'display technology', leading to improved image quality, energy efficiency, customizable color emission (Red, Green and Blue ie. RGB) and enhanced brightness for high-quality visuals, wider color gamut and more vivid, lifelike images (LCDs, LEDs even heavy-metal-free QLEDs).

Finally, different CQDs and hetero-atom doped-CQDs have been explored for lighting applications which will provide thrilling future-challenges and opportunity to the society.

Keywords: Quantum dots, Display technology, photo-luminescence, fluorescent ink, anti-counterfeit

I. Introduction

Display technology has been revolutionized and undergoing rapid advancements, driven by innovative quantum dots (QDs) materials, leading to improved image quality, energy efficiency, high-resolution, more vibrant and new generation of displays. These advancements have impacting various applications, from consumer electronics (smartphones, televisions) to digital signage, and even medical devices (Z. Chen, 2023, J. Yang, 2020).

Now-a-days, quantum dot technology have been developed in such a way that it can produce specific colours by tuning the size of the nano-materials which leads to displays with vibrant, high-quality images and lighting solutions that are more energy-efficient and colour-accurate (P. Surendran, 2020, S. Pandiyan, 2020). It can also offer customizable colour emission and enhanced brightness for high-quality visuals, wider colour gamut and more vivid, lifelike images. This allows for more saturated colours and a wider colour gamut compared to traditional displays and lighting, which use colour filters that can lead to some light loss. Recently, to improve colour accuracy, brightness, and power efficiency, QLED (Quantum Dot Light Emitting Diode, QD LED) display technology has now been primarily used in televisions, monitors and can create flexible and transparent displays, enabling the development of foldable phones, curved screens,

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and wearable devices (K. Yang, 2025). Not only electronics domain, quantum dot technology has been developed for light-emitting and biological luminescent application offering enhanced capabilities in early cancer detection, multi-color cellular imaging, targeted drug delivery, and improved treatment efficacy (Y. Huang, 2020) (Figure 1).

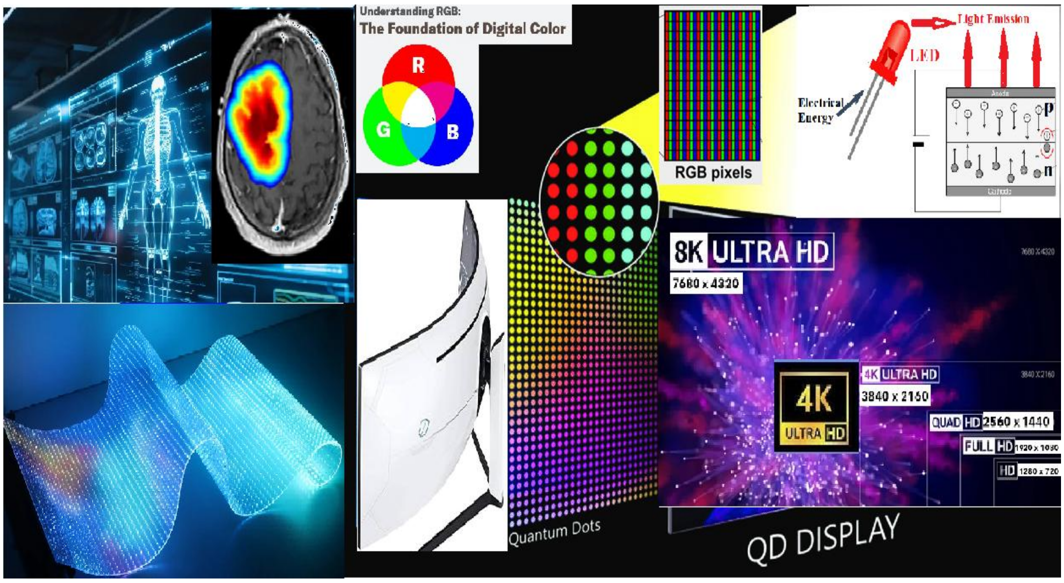

Figure 1. Illustration of quantum dots (QDs)-based different display-technology application

Quantum dots (QDs) are basically tiny inorganic particles, most of the cases nano-sized (2-10 nm) semiconductor or conductor, which have been considered as exceptionally beautiful in the field of material science domain owing to possessing unique optical and electronic characteristics (A. K. Dutta, 2025, M. A. Mimona, 2025). The term “quantum” refers to their physical properties that can show ‘quantum confinement phenomena’ which only happens on nano-scale sized materials, not appear in bulk-material. This effect enables QDs unique behaviour under the light exposure. This particle size range is equivalent to just a few to a few dozen atoms across and that small size makes them exhibiting unique optical and electronic properties, including the ability to emit different colours of light ranging from red to blue when exposed to light.

The colour they emit depends upon the size of the particle and the emitted light’s wavelengths can be precisely controlled by simple adjusting the particle size of the QDs during laboratory synthesis process. When the dimensions of a system(material) have been reduced to the nano-scale level, specifically when those dimensions approaches to Bohr radius or fall below the Bohr radius of an exciton, electrons and holes become restricted/confined in small spaces, behave as quantum mechanical particles, leading to a quantization of energy levels, meaning the energy of these particles is no longer continuous but rather exists in discrete levels and changes in the material's optical and electronic properties. Consequently, the band gap, which determines the particular wavelength of light absorbed or emitted by a semiconductor, can be tuned by controlling the size of the material.

Smaller sizes generally lead to a larger band gap and shorter emission wavelengths (Figure 2). Since very old days, so many scientists have paid considerable attention to engineer the dots from bulk materials that include gold to graphene to cadmium, and create their colour by controlling their size (M. A. Cotta, 2020). The tiniest particles, in which electrons are most tightly confined, emit blue light. Slightly larger particles, in which electrons bounce around a longer wavelength, emit red light.

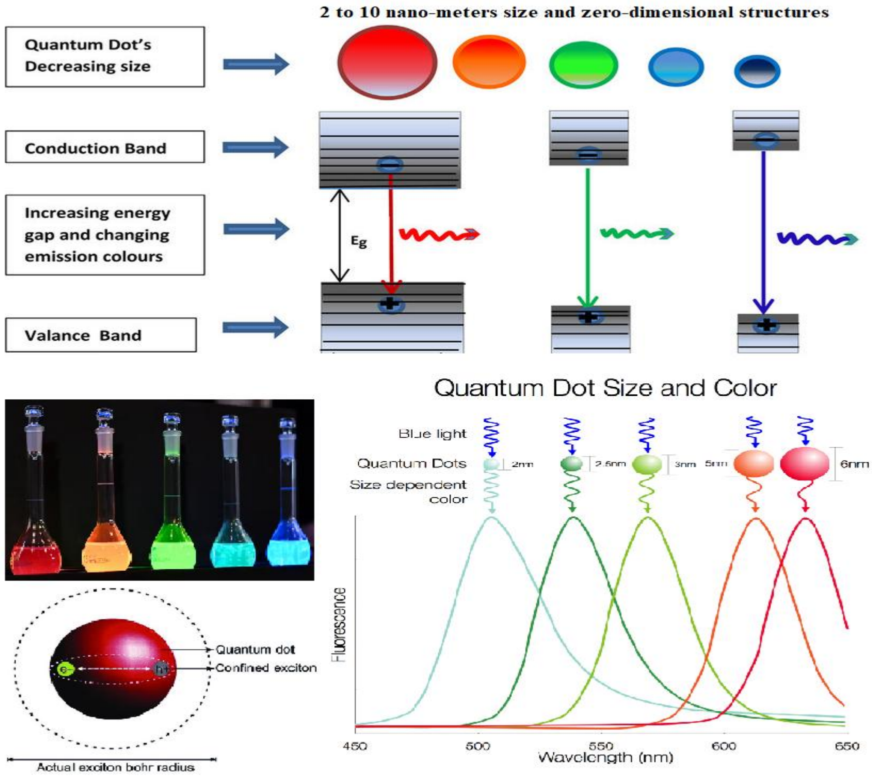

Figure 2. Colloidal quantum dots irradiated with light. Different-sized QDs emit diverse colours of light owing to quantum-confinement.

With development of science and technology, the ability to tailor the properties of the QDs makes them a truly exceptional benefits in diverse fields like solar-energy conversion, catalysis, solid-state lighting, display technology, sensing, medical diagnostics, bio-imaging, image-guided surgery, bio-medical etc. The 2023 Nobel Prize in Chemistry has been awarded to Moungi G. Bawendi, Louis E. Brus, and Aleksey I. Ekimov for the discovery and synthesis of QDs (L. M. Liz-Marzán, 2023). Prof. Ekimov and Prof. Brus independently discovered quantum dots in the late 1980s and early 1990s and linked their size to their optical properties, while in 1993, Prof. Bawendi revolutionised the chemical production method for synthesizing them in laboratory with uniform size and quality, resulting in almost perfect particles. Their work has led to a revolution in nanotechnology and has made possible many new technologies. QDs has been firstly introduced in 2013 in TV display by SONY. Since then, significant innovative discovery in quantum dot technology has enabled further development and

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now spread their light from computer monitors, television screens (based on QLED technology) and LED lamps.

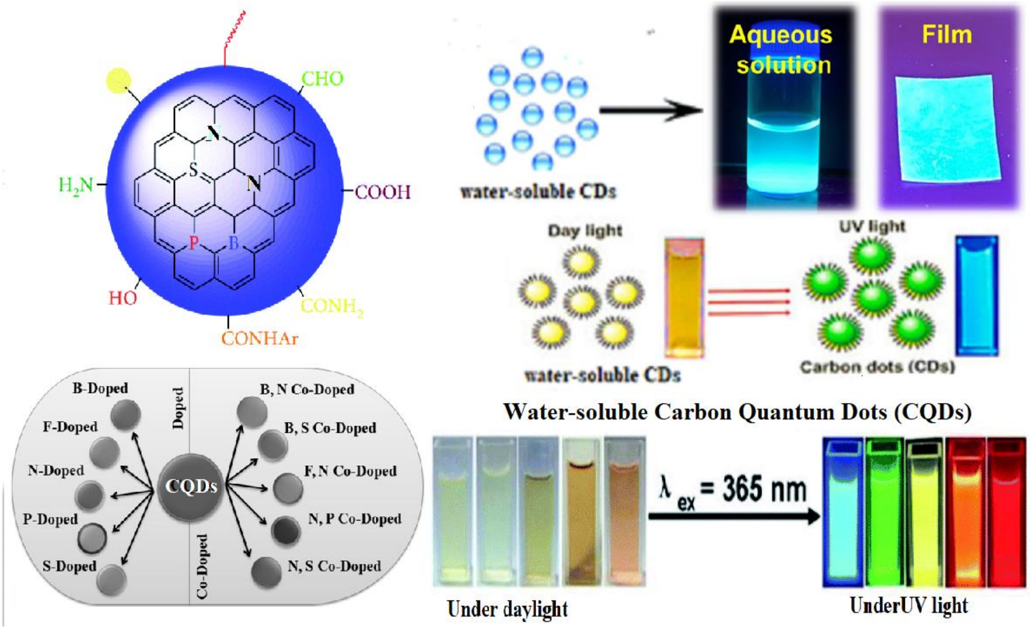

Figure 3. Schematic representation of pristine carbon quantum dots (CQDs) and different heteroatom doped-CQDs

Since very old days, so many scientists have paid considerable attention to engineer the dots from bulk materials that include gold to graphene to cadmium, and create their colour by controlling their size (M. A. Cotta, 2020). Among the different quantum dots materials, carbon-based quantum dots (CQDs) become 'Revolutionary Materials' today in material science domain, which have been developed for enormous attainable applications (R. Verma, 2024) (Figure 3). Now-a-days, this interesting technology has been incorporated into different industrial sectors and everyday consumer product to revolutionize and improve product efficiencies and performances across various domains. Heteroatom doping of CQDs with nitrogen (N), oxygen (O), sulphur (S), phosphorous (P), Boron (B) etc. can significantly enhances the display through improving colour purity, brightness, and optimizes the CQD's bandgap and electron density, leading to tuneable photoluminescence properties, better light emission and charge transport properties (Figure 3). Heteroatom doping can modify the electronic structure of CQDs in such a way that the researcher can develop high-fluorescent or high quantum yield (QY) and high photo-stable CQDs for excellent fluorescence performance, brighter-stronger emission of specific colors. This is particularly useful in QLED (Quantum Dot LED) displays, where CQDs can convert blue light from a backlight into red, green, and blue light for a wider colour gamut.

QLEDs, which utilize CQDs, are emerging as a strong contender in high-end display technology, offering excellent colour realism and longevity. Again, their discrete optical properties, particularly their special ability to emit bright photoluminescence (PL) covering the entire visible-near infrared (NIR) spectral range, further enhances their potential application in cancer treatment, for bio-imaging, sensing, diagnostics, therapeutics, and other bio-medical, optical, electronics and materials science applications. Introducing element like N, O or S into the carbon framework and surface-modification technology (with specific group) can shift the emission towards longer wavelength (red-shifted) as well as increase the quantum yield (QY). Variation of N and O content in carbon core can affect the size of Π-conjugated domain, can improve electron delocalization, the electron transport properties, longer carrier lifetime, broaden absorption region. Now-a-days, researcher have paid considerable attention to develop interesting Red, Green, Blue and NIR emitting different CQDs to improve full-spectrum-light driven electronic devices and multi-color cellular imaging. The N-doped CQDs (N-CQDs) have attracted significant attention in recent time for improving fluorescence performance and broadening their applications. H. Zhang, 2022 have proved that huge amount of C=O functionalization on a CQDs surface is main responsible for their pure red-emission (at 600 nm) generated from n-Π* and Π-Π* excitation of C=O and C=N bonds and that newly designed CQDs have been successfully utilized for various luminous applications. J. Yang, 2020 had developed red/ NIR emissive CQDs where effective Π-conjugated system have been generated with N-heterocycle and aromatic rings, where Nitrogen plays crucial role in charge carrier and can transfer their electrons to the analyte molecules during analytical application and detection of the target analyte. Not only single blue, green or red emission, K. Jiang, 2015 has developed such type of interesting Red, Green and Blue (RGB, the three primary color) bright-emitting CQDs upon single 365 nm wavelength UV irradiation so that they can be used in Full-colour emissive or multi-color emissive material for multi-color cellular imaging (Figure 3).

With these evidences, this article focused on the development of different carbon quantum dots (CQDs) materials for lighting, display, solar cell, sensing and biomedical applications through simple one-step pyrolysis or carbonization synthesis approach from various laboratory chemicals as well as natural bio-mass, plant-husks, domestic organic waste etc. as carbon precursors. It has been discussed, how hetero-atom doping with N, O, P, S etc., on pristine CQDs can tailor the electronic structure and properties of CQDs, leading to improved image quality, energy efficiency, customizable color emission and enhanced brightness for high-quality visuals, wider color gamut and more vivid, lifelike images. It has been highlighted about recent advances in the development of efficient Red, Green and Blue (RGB) emitting heavy-metal-free QLEDs. Finally, different CQDs and hetero-atom doped-CQDs have been explored for lighting and fluorescence guided anti-counterfeit applications.

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II. Basic principle of tailoring CQDs properties through heteroatom doping

Heteroatom doping is a powerful tool for tailoring the electronic structure and properties of CQDs, enabling a wide range of applications in areas like bioimaging, sensors, and catalysis. Now-a-days, researchers have successfully tailored display technology through doping strategy, enhancing fluorescence properties, colour tunability, and overall performance. Like defect-engineering modalities, heteroatom doping also can improve the optical and electronic properties of carbon quantum dots (CQDs) by introducing new electronic states within the band gap of CQDs, effectively narrowing or widening it. Doping creates defects and new electronic states within the carbon structure, allowing for the fine-tuning of CQD properties for applications like sensors, bio-imaging, and electronics. This can shift fluorescence emission wavelengths, change luminescence intensity, and tune conductivity.

When heteroatoms such as nitrogen (N), oxygen (O), sulphur (S), boron (B), or phosphorus (P) etc. have been introduced into carbon framework, new energy states (defective energy levels) have been generated near the conduction-band (CB) or near the valence-band (VB) within the electronic structure (band-structure) of CQDs (Figure 5), influencing the position of the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) levels, manipulating their electronic structure, optical properties (such as fluorescence), and even their chemical reactivity. This allows for the creation of CQDs with tailored characteristics for specific applications. Doping also can promote radiative recombination of electron-hole pairs, leading to increased photoluminescence intensity and higher QY. Nitrogen doping is a common strategy to enhance the optical properties of CQDs. Nitrogen atoms can replace carbon atoms in the CQD lattice, introducing a lone pair of electrons and increasing the electron density, leading to improved fluorescence and higher QY. Nitrogen doping can lead to a decrease in the band gap due to increased electron density and the introduction of new energy levels.

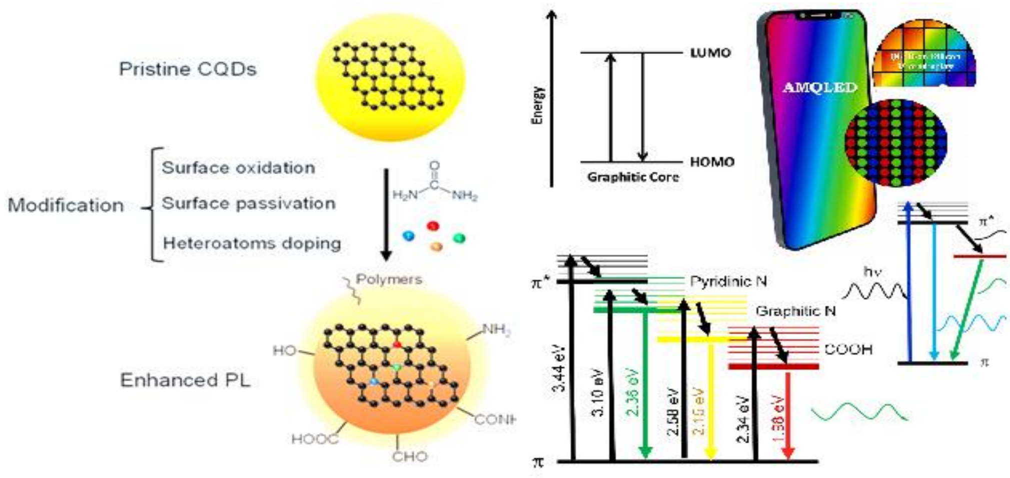

Figure 5. Tuneable fluorescence emission of CQDs with different heterogeneous atom doping and introduction of new energy states inside the HOMO-LUMO bandgap

Heteroatom doping of carbon quantum dots (CQDs) significantly tailors display technology by enhancing fluorescence properties, colour tunability, and overall performance. In recent years, it has been proved that doping with heteroatom nitrogen (N), oxygen (O), sulfur (S), boron (B), or phosphorus (P) is an effective approach to improve the optical and electronic performance of CQDs via tuning their carbon skeleton matrices and the chemical structures (X. Kou, 2020). Again, heteroatom doping can significantly increase their quantum yield (QY). This is because doping with elements like N, S, P, B etc. can alter the electronic-structure of the CQDs, enhancing their capability to absorb-emit light. This leads to a higher probability of radiative transitions, resulting in improved quantum yields. Despite difference in chemical structure among various dopants, maximum doped CQDs exhibit a similar absorption profile, characterized by a strong and broad absorption band ranging from 200 nm to 600 nm, which is assigned to the Π- Π* transitions of C=C and C-C bonds in aromatic Π systems of CQDs.

III. Display technology evolution: inception to modern era

During Revolutionization of display-technology, two important parameters, RGB and CRI have been monitored in artificial lighting systems. RGB (Red, Green, Blue) is the foundation for how colours are displayed on screens, while CRI (Colour Rendering Index) measures how accurately a light source displays colours compared to natural light. RGB is more fundamental as it is the colour-model used by all digital displays, while CRI is a metric for evaluating the quality of light's colour reproduction (Figure 6). Essentially, RGB defines how colours have been created, and CRI indicates how well those colours have been reproduced by a light source. Since the mid-19th century, RGB colour model have been used to represent colours on digital displays. In 1861, James Clerk Maxwell first demonstrated the RGB colour-model as an additive colour model (through his experiments in colour photography), meaning colours have been created by adding different intensities of red, green, and blue light, which were then projected together to create a full-colour image. When all three colours have been combined at full intensity, they produce white light. Conversely, when all three colours are at zero intensity, the result is black. By varying the intensity of these three colours, a vast spectrum of colours can be created (principle behind additive colour mixing) (H.S. Fairman, 1997). Over time, the RGB-model became fundamental to the development of electronic devices like televisions-computer displays, cameras, and other electronic imaging systems.

Now-a-days, some semiconductor nanocrystals, quantum dots (QDs), have been widely used to create the RGB colour-model in display technology (X. Zhang, 2025). Carbon Quantum Dots (CQDs), when excited by light or electricity, can successfully emit pure red, green, and blue light, which can then be combined to create a wide range of colours in the RGB spectrum (including white), improving display brightness and colour gamut compared to traditional methods. Researchers have successfully synthesized CQDs in such a way that the emission colour of the CQDs can be tuned by controlling their size, surface chemistry, and doping with other elements. These CQDs have been incorporated into displays, either as part of the backlight in LCDs or as the light-emitting layer in QD-OLED or QLED displays, to produce a wide range of colours with high efficiency and colour purity. In this way, QLED becomes foundation of next-generation display technology to meet the personalised demands of advanced applications, such as mobile phones, wearable watches, virtual/augmented reality, micro-projectors, and ultrahigh-definition TVs (X. Chen, 2024). White light emitting diodes (WLEDs) become another major part of artificial lighting systems across the globe. In commercially available white-LEDs, generally costly rare earth lanthanides-based materials have been used but, after discovery of quantum dots (QDs), they have been enormously applied in white light emitting diodes (WLEDs) and WLEDs with high colour rendition (CR Index) and high demand (M. Sami, 2024).

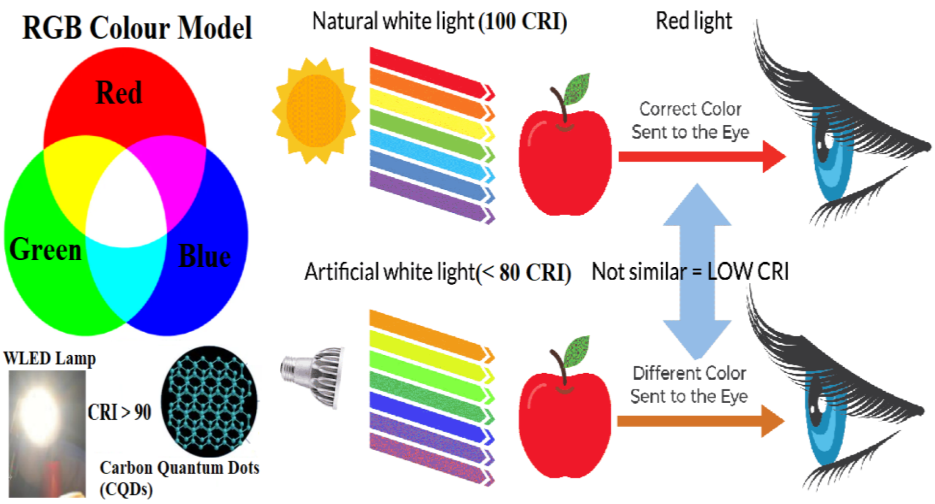

Figure 6. Understanding CQDs-based RGB colour model with high CRI

Very recent, Carbon quantum dots (CQDs) have been engineered to achieve high colour rendering index (CRI) values, particularly in WLEDs and QD-WLEDs (M. Perikala, 2021). CRI is a measure of how accurately a light source reveals the colours of objects compared to a reference light source, like daylight (Figure 6). A high CRI indicates that a light source can accurately reproduce a wide range of colours, similar to how they would appear under natural daylight. Some CQD-based WLEDs have achieved CRIs exceeding 90, and even reaching 94 or higher, making them comparable to or better than traditional quantum dot (QD) WLEDs (using heavy metals like cadmium and lead). High refresh-rate monitors with quick response also becomes other premium features. The combination of high refresh rates(measured in Hz) and fast response times (usually measured in milliseconds, ms and some as low as 0.03ms) in QD-based displays makes them particularly beneficial for gaming, as they deliver a smoother, more responsive, and immersive gaming experience. Some display models reaching 175Hz or even 360Hz high refresh rates, combined with fast response times (some as low as 0.03ms), are particularly beneficial for gaming, providing smoother motion and reduced blur. High Dynamic

Range (HDR) on monitors enhances visual quality by expanding the range of colours and brightness levels, creating more realistic and vibrant images compared to standard monitors. HDR content displays details in both bright and dark areas of a scene simultaneously, unlike standard monitors which may lose detail in one area when focusing on the other. This results in a more immersive and detailed viewing experience by delivering more vibrant, realistic images with greater contrast and detail.

In modern devices (smartphones tablets, monitors), high-resolution displays are increasingly in demand. High resolution refers to the level of clarity in an image, directly affects the sharpness and quality of the visual content, which is represented by the number of pixels (PPI) or dots per inch (DPI). Consumers are seeking sharper, more detailed visuals compared to older, lower resolution displays. That modern devices increasingly utilize resolutions like Full HD (1920×1080), Quad HD (2560×1440), and even 4K (3840×2160). CQDs becomes very promising material for high-resolution displays due to their size, tuneable emission, and compatibility with other technologies. CQDs can be very small, have been widely used for the creation of tiny pixels (which is essential for high-resolution displays) and have been patterned into dense arrays, enabling high pixel density and achieving resolutions like 15,000 PPI (higher PPI means more pixels are packed into each inch, resulting in a sharper, more detailed image). Most modern smartphones and monitors have PPI values ranging from around 300 to 500 for good visual quality. The high pixel resolution is emerging as one of the key parameters for the next-generation displays. Despite the development of various quantum dot (QD) patterning techniques, achieving ultrahigh-resolution (>10,000 pixels per inch (PPI)) and very recent, with continued research and development in this area, quantum dot (QD) technology, including carbon quantum dots (CQDs), lead to even more advanced 4K/8K displays (C. Luo, 2024). QLED 32", 43", 55", 75" or even 105" 4K/8K displays with now becomes popular for TVs, monitors, and other devices where high-quality visuals are desired, such as for gaming, movies, and professional content creation. 4K display resolution, also known as Ultra High Definition (UHD), refers to a horizontal display resolution of approximately 4,000 pixels. The most common 4K resolution is (3840 × 2160) pixels (3840 pixels horizontally and 2160 pixels vertically, totalling over 8 million pixels), which is four times the resolution of Full HD (1920 × 1080). This higher pixel density results in sharper images and more vibrant colours, making it popular for tasks like video editing, gaming, and graphic design. 4K resolution, especially when paired with a high refresh rate (e.g., 120Hz or 144Hz), can significantly enhance the gaming experience with smoother motion and sharper visuals. Samsung Electronics Co., Ltd. has also incorporated Quantum Dot technology into curved displays, with a curvature like 1800R (R, indicating the radius of the curve's arc), which have been designed with a concave curve with an ultra-wide 178-degree viewing angle to mimic the natural curvature of the human eye, potentially reducing eye strain and creating a more wraparound effect and immersive viewing experience anywhere within a given room. Carbon quantum dot curved displays can achieve high refresh rates, with some models reaching 175Hz or even 360Hz. These high refresh rates, combined with fast response times (some as low as 0.03ms), are particularly beneficial for gaming, providing smoother motion and reduced blur.

IV. Fluorescent ink and anti-counterfeiting ink imaging

Fluorescent ink imaging uses inks containing light-absorbing molecules that emit visible light when excited by UV or other wavelengths, allowing for the creation of glowing images under specific lighting conditions, marking confidential documents (writing letters), currency, jewellery and drawing patterns (coding) to prevent fraud (Figure 10). This technology provides enhanced visualization of invisible structures, aids in anti-counterfeit applications. Quantum dots based fluorescent ink become more promising owing to their size-dependent fluorescence, exceptional photostability (resisting bleaching), and high quantum yield. Now-a-days, superior fluorescence (highly luminescence) performance of CQDs have been used to encode information that is only visible under specific conditions and becomes promising for forensic applications like fingerprint visualization, toxicological analysis, and anti-counterfeit interventions. CQDs have been integrated into fingerprint-developing powders for improved detection and analysis both on a glass slide and filter paper under light (365 nm) irradiation (Figure 10) (D. Fernandes, 2015). Incorporating heteroatoms like nitrogen (N-CQDs) can enhance photostability by altering the chemical composition and surface steric effects, leading to better performance under UV exposure and thermal stress.

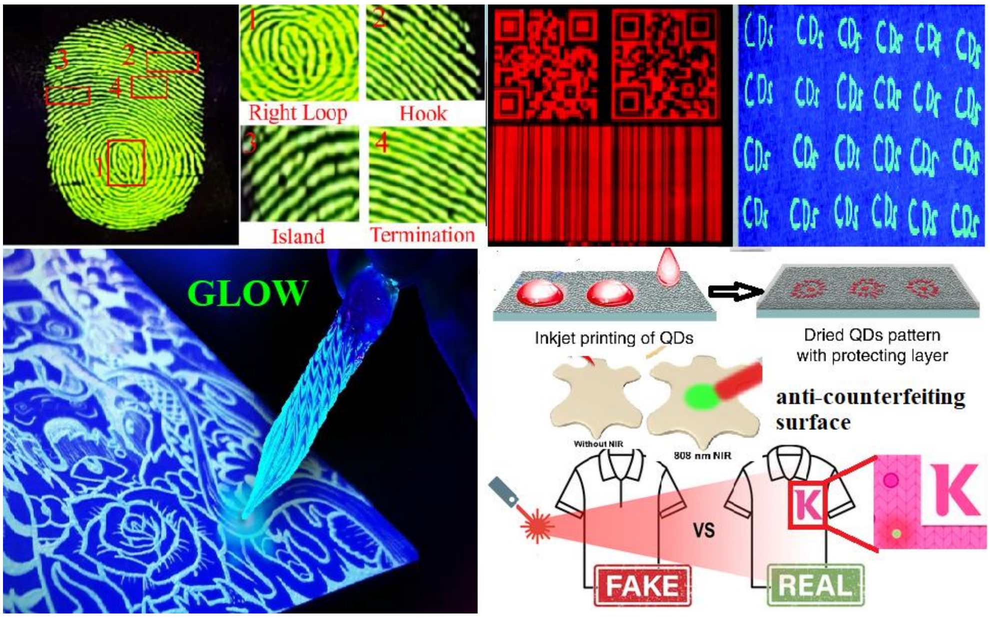

Figure 7. Magical fluorescent-ink for instantaneous imaging of different aids in anti-counterfeit applications

By utilizing the RGB emission of heteroatom doped-CQDs, some advanced anti-counterfeiting ink or security ink have been fabricated for security printing where the inks have been customized to emit different colours and are incorporated with unique physical structures or "physical unclonable functions" (PUFs) to create full-colour fluorescence security labels and multi-level security features. CQDs as long persistent phosphors have been used in anti-counterfeiting applications, which involve technological solutions like holograms, QR codes, and RFID tags for product authentication, as well as legal actions, public awareness campaigns, and collaboration with customs and law enforcement agencies to protect intellectual property and ensure consumer safety. It has been found that B and N co-doped CQDs could be incorporated into ink (fluorescent ink) for anti-counterfeiting, capable of functioning as a new generation of cost-effective barcodes and security nanotags for object authentication and anti-counterfeit applications (Y. Guo, 2017). Researchers also explored the potentiality of N and S co-doped CQDs for fluorescent ink for image formation, including handwriting, inkjet printing, and transfer printing to increase security features like holograms, watermarks, tamper-evident seals, unique product identifiers (such as RFID tags), and track-and-trace systems to verify authenticity and safeguard supply chains (Y. Liu, 2019). The security pattern has been created by selectively depositing CQDs onto the surface of an object (Figure 10) to form a unique, unclonable identifier, leveraging the CQDs' inherent fluorescent properties for authentication. Sometimes, ‘digital fingerprint’ has been fabricated using combination of CQDs-based digital pattern and ‘Artificial Intelligence’-based authentication strategy (AI-decodable, unclonable), that is unique to each device, cannot be copied or predicted, and can be used to generate unique cryptographic keys for secure authentication, data encryption, and device anti-counterfeiting.

With development of science and technology, CQDs-based inks have been made to be long-lasting and fade-resistant by optimizing the synthesis and encapsulation process, often by incorporating the CQDs into stable matrices like salt crystals or polymers and protecting them from oxidation and environmental factors. Embedding quantum dots (QDs) within a polymer matrix can significantly improve their photostability, providing a long-lasting, non-fading fluorescent ink. The polymer acts as a protective layer, preventing aggregation, oxidation, and other environmental factors that cause QDs to degrade and lose their fluorescence over time.

V. Challenges and Future Perspectives in the Field of Display and Bioimaging Using Heteroatom Doped CQDs

Recent advances in scientific-research have shown fascinating solutions that might revolutionize ‘display technology’ in the future leading to improved image quality, energy efficiency, customizable color emission and enhanced brightness for high-quality visuals, wider color gamut and more vivid, lifelike images. With the development of science and technology, several challenges can be overcome using different CQDs and hetero-atom doped-CQDs in the field of lighting and fluorescence guided anti-counterfeit applications which will provide exciting future opportunity for the sake of society. Another great challenge has been created to the researchers to synthesize such imaging and therapies material that can generate bright-fluorescence performance in the longer red and NIR region to utilise the Red-NIR-light. Another great challenge has been created to the researchers to develop such efficient Red, Green and Blue (RGB) emitting heavy-metal-free QLEDs for primarily used in televisions, monitors and can create flexible and transparent displays, enabling the development of foldable phones, curved screens, and wearable devices in future.

VI. CONCLUSION

From the present study, it has been concluded that innovative different pristine carbon quantum dots (CQDs) as well as heteroatom doped-CQDs have successfully revolutionize 'display-technology' and their unique optical, electronic properties make them promising for next-generation lightning and imaging. Heterogeneous atom doping (N, O, P, S etc.) on pristine CQDs, can significantly enhances the display through improving colour purity, brightness, and optimizes the CQD's bandgap and electron density, leading to tuneable photoluminescence properties, better light emission and charge transport properties. Tunable highly-fluorescent CQDs have been successfully explored both as lightning and imaging agents, molecular-imaging probes for development of efficient Red, Green, and Blue (RGB) emitting heavy-metal-free QLEDs. It has also been investigated the interesting Red, Green, Blue and NIR emitting different CQDs to create the RGB colour-model in display technology as well as to improve full-spectrum-light driven multi-color fluorescent-ink imaging which will provide thrilling future-challenges and opportunity to the society.

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