OPEN ACCESS
**Haya: The Saudi Journal of Life Sciences**
Abbreviated Key Title: Haya Saudi J Life Sci
ISSN 2415-623X (Print) | ISSN 2415-6221 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

**Review Article**

# Exploring the Frontier of Nanotechnology: A Comprehensive Review on Carbon Nanoparticles and Carbon Nanodots and their Diverse Applications

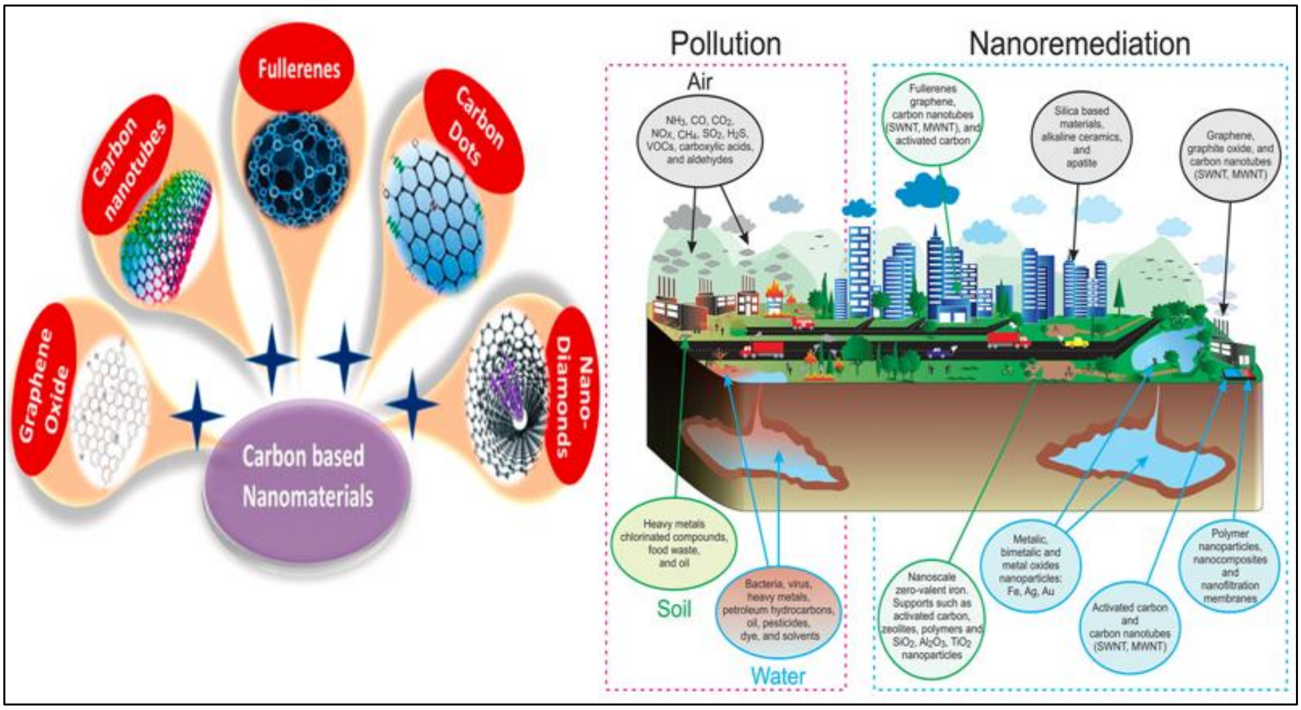
Nimra Sardar[1*], Syed Muhammad Jawad Raza Rizvi[2], Amna Asif[3], Shoaib Muhammad[4], Khadija Ali[5], Iqra Kanwal[3], Maneeb Ur Rehman[6], Mohsin Saleem Ghouri[7], Iffat Lattif[8]

[1]Department of Botany, Pir Mehr Ali Shah (PMAS) Arid Agriculture University Rawalpindi, Pakistan
[2]Department of Environmental Sciences, University of Lahore, Punjab Pakistan
[3]Department of Chemistry, University of Agriculture Faisalabad, Punjab Pakistan
[4]Department of Mathematics and Physics, University of Campania "Luigi Vanvitelli" Caserta, Italy
[5]Department of Chemistry, Government College University Faisalabad, Punjab Pakistan
[6]Department of Physics, Faculty of Basic and Applied Sciences (FBAS), International Islamic University (IIU), H-10, Islamabad, 44000, Pakistan
[7]Department of Chemistry, Government Murray Graduate College, Sialkot
[8]Centre of Solid-State Physics, Punjab University Lahore, Pakistan

**DOI:** https://doi.org/10.36348/sjls.2025.v10i03.005 | **Received:** 06.02.2025 | **Accepted:** 14.03.2025 | **Published:** 17.03.2025

***Corresponding author:** Nimra Sardar
Department of Botany, Pir Mehr Ali Shah (PMAS) Arid Agriculture University Rawalpindi, Pakistan

## Abstract




**Graphical Abstract**

Carbon nanoparticles (CNPs) and carbon nanodots (CNDs) represent a revolutionary new frontier in nanotechnology with their distinct structural, optical, and chemical characteristics. Their unique properties have allowed them to be incorporated into various scientific and industrial applications. This comprehensive study delves into the synthesis, characterization, and functionalization of CNPs and CNDs, exploring the concepts underlying their remarkable qualities, which include excellent photostability, adjustable fluorescence, biocompatibility, and simplicity of surface modification. These nanostructures have various industrial applications, including electronics, energy, environmental research, and healthcare. Their potential to transform healthcare is fascinating, highlighted by their use in photothermal treatment, bioimaging, and drug delivery systems in biomedicine. The ability of CNPs and CNDs to tackle urgent ecological issues is further demonstrated by their application in environmental restoration, including water purification and pollution detection. The use of CNPs and CNDs in optoelectronics and energy storage devices like supercapacitors and batteries further illustrates their value in developing efficient and sustainable technologies. Even with these encouraging advancements, issues remain to be resolved, such as maximizing large-scale manufacturing, maintaining consistency, and dealing with long-term environmental effects. To overcome these obstacles and realize the full potential of carbon-based nanomaterials, this analysis highlights the necessity of multidisciplinary cooperation, which will eventually open the door for creative answers to pressing global issues.

**Keywords:** Carbon nanoparticles, Carbon nanodots, Nanotechnology, Nanomaterials, Quantum dots, Biomedical applications, Optoelectronics, Fluorescent nanomaterials, Antibacterial properties, Surface functionalization, Carbon-based nanostructures, Sustainable Nanotechnology.



## INTRODUCTION

Carbon-based nanostructures are a noteworthy class of nanomaterials with unique physicochemical features and a wide range of uses, especially carbon nanoparticles (CNs) and carbon nanodots (Georgakilas *et al.,* 2015). CNs are typically spherical or almost spherical particles that range in size from a few to several hundred nanometers and are mostly made of carbon. They are appropriate for energy storage, catalysis, and composite materials due to their excellent mechanical strength, thermal conductivity, and chemical stability (Yang *et al.,* 2017). CDs, conversely, are incredibly tiny carbon-based structures with sizes less than 10 nm and are sometimes regarded as a subset of carbon nanoparticles. Strong fluorescence, which results from surface functional groups and a phenomenon called 'quantum confinement, 'is one of the distinctive optical characteristics of CDs (Chen *et al.,* 2019). Quantum confinement refers to reducing the dimensions of a material to a few nanometers or less, which leads to changes in its electronic properties. Because of their fluorescence tunability, CDs are now important components in drug delivery, biosensing, and bioimaging applications. Their structural arrangement and functionalization are the primary distinctions between CNs and CDs. While CDs have a well-defined graphitic core with several surface functions, contributing to their excellent solubility in aqueous environments and biocompatibility, CNs are frequently amorphous or partly crystalline (Zhou *et al.,* 2022). Furthermore, CDs may be produced from various precursors, such as biomass and organic molecules, using chemical oxidation, pyrolysis, and hydrothermal treatment, providing sustainable manufacturing routes. In contrast, CNs frequently call for more energy-intensive procedures like chemical vapor deposition or arc discharge (Sonowal *et al.,*2024). These variations show how versatile CDs are as a more environmentally friendly option for biological and environmental applications. At the same time, CNs are still essential in fields that demand better mechanical and conductivity qualities. These carbon-based nanostructures' convergence in cutting-edge research highlights their complementing functions. Facilitating advancements in interdisciplinary domains, including environmental science, energy, and medicine (Tariq *et al.,* 2024).

An important technical turning point in data storage and audio playback history was the discovery and creation of compact discs (Rothenbuhler *et al.,* 2012). The adventure officially began when optical technology and digital storage became feasible in the late 1960s. James T. Russell laid the groundwork for optical media in 1965 by creating a prototype that used light to read recorded data, hence pioneering early optical disc systems. Nevertheless, breakthroughs did not appear until the 1970s. Two significant electronics companies, Philips and Sony, led the joint creation of the CD (Hachiya *et al.,* 2010). Together, they combined Sony's digital encoding technology with Philips' optical disc knowledge to develop a standardized format for digital audio discs in 1979. Compared to analog media like vinyl and cassette tapes, CDs offered previously unheard-of audio quality, portability, and longevity, completely changing the music business (Ashbourne *et al.,* 2020). With the invention of the CD-ROM in 1985, the technology swiftly expanded into data storage, enabling computers to store vast volumes of digital data. The usefulness of optical discs was significantly expanded by the 1990s when writable CDs (CD-R) and rewritable CDs (CD-RW) allowed users to record and erase data (Carriere *et al.,* 2000). Although DVD and Blu-ray technology eventually eclipsed CDs in later decades, their influence on digital storage and playback is still a pivotal moment in the history of contemporary media, inspiring formats and standards that are still in use today. As a result of this collaboration, the Red Book standard was created in 1980, and the digital and physical properties of the CD were outlined (Byers *et al.,* 2003). Billy Joel's 52nd Street was the first album to be issued in the new format, and the first commercial CDs and CD players were introduced in 1982 (Bellman *et al.,* 2020).

The pressing need to address global environmental issues, resource scarcity, and the growing desire for more environmentally friendly industrial processes are the main drivers of the growing interest in sustainable synthesis approaches (Sheldon *et al.,* 2017). Conventional chemical synthesis frequently uses dangerous chemicals and energy-intensive processes, which results in large waste and greenhouse gas emissions. On the other hand, sustainable synthesis aims to reduce its adverse environmental effects by using creative strategies, including energy-efficient procedures, green solvents, and renewable feedstocks (Kar *et al.,* 2021). Catalysis, specifically biocatalysis, and heterogeneous catalysis, is essential to achieving these objectives because it increases reaction efficiency and selectivity while lowering hazardous chemical requirements. The toolset for sustainable chemistry has been further broadened by developments in photochemistry and electrochemical synthesis, which allow reactions to occur in mild environments and use clean energy sources such as power generated by sunshine or renewable resources (Thomas *et al.,* 2014). Additionally, atom-economical reactions like those based on click chemistry have gained popularity because of their capacity to optimize resource use and reduce waste. The combination of computational tools, machine learning, and artificial intelligence is also transforming the area by speeding up the identification of environmentally favorable reaction routes and improving process parameters (Zhu *et al.,* 2022). Recognizing the ethical and financial advantages of these practices and their compatibility with global sustainability goals like the Sustainable Development Goals (SDGs) of the United Nations, industries ranging from materials research to medicines are adopting them at an increasing rate. Growing consumer awareness and more stringent environmental laws worldwide have further encouraged research and innovation in this field, leading to a concerted effort by academia, business, and policymakers to reshape the future of chemical manufacturing using sustainable synthesis techniques (Idoko *et al.,* 2024). To assess how using carbon nanoparticles in different businesses affects sustainability and the environment. To investigate the many uses of CNPs and CNDs in industries including electronics, energy storage, medical, and environmental cleanup. To evaluate new developments in CNP and CND synthesis and functionalization for improved performance in specific applications.

**Beyond Conventional Carbon Nanodots, Hybrid Innovations**

The evolution of CDs has expanded beyond their conventional forms, giving rise to hybrid innovations that integrate metallic and non-metallic elements to enhance their functional properties (Liu *et al.,* 2024). Researchers have significantly improved their optical, electronic, and catalytic performance by doping CDs with nitrogen, sulfur, and various metals. These dopants modify the electronic band structure and introduce surface-active sites, making the nanodots suitable for sensing, energy storage, and bioimaging applications. Alongside CDs, GQDs have emerged as strong contenders, offering superior charge transport and photoluminescence properties due to their well-ordered graphene structure. However, while GQDs excel in certain areas, their synergy with CDs creates a unique platform for developing hybrid systems that combine the best of both nanostructure's enhanced fluorescence and chemical stability and tunable electronic properties (Mishra *et al.,* 2024). The development of dual-functional carbon nanodots guides innovation toward multifunctional applications beyond individual functionalities. These cutting-edge materials highlight the potential of hybrid nanodots to address challenging issues in nanotechnology by combining the capabilities of bioimaging and medication delivery or photocatalysis and energy storage. The interaction between competition and cooperation in CDs and GQDs reveals a fascinating frontier where hybrid techniques alter the possibilities of nanoscale materials (Liu *et al.,* 2020).

**Bio-Inspired Nanotechnology Learning from Nature**

Utilizing nature's design principles, bio-inspired nanotechnology creates novel nanomaterials with improved functionality, especially in carbon dots (Dutta *et al.,* 2022). Imitating natural photosynthetic processes is one of the most promising strategies for enhancing energy conversion and collection. CDs have been investigated as artificial photosensitizers, improving light absorption and charge transfer efficiencies similar to chlorophyll-driven photosynthesis in plants because of their superior optical qualities and biocompatibility. The synthesis of CDs from natural precursors such as plant leaves, coffee grounds, and pineapple peels further supports the sustainable nature of bio-inspired nanotechnology. The green synthesis of CDs with adjustable fluorescence characteristics and no environmental effect is made possible by the abundance of carbon and nitrogen sources in these organic waste products (Liu *et al.,* 2019). Additionally, inspiration from bioluminescent creatures has motivated the creation of CDs for bioimaging and sensing applications. In order to follow biological processes in real-time, scientists have attempted to reproduce the luminous qualities of several marine species, including fireflies and jellyfish, which are produced by enzymatic activities. Functionalized CDs are excellent for biomedical imaging, biosensing, and targeted drug administration because of their intense fluorescence, excellent photostability, and low toxicity. Bio-inspired CDs are developing into adaptable nanomaterials with revolutionary potential in energy, environmental, and medical applications by taking inspiration from nature's complex molecular structures and adaptive processes (Harun-Ur-Rashid *et al.,* 2023).

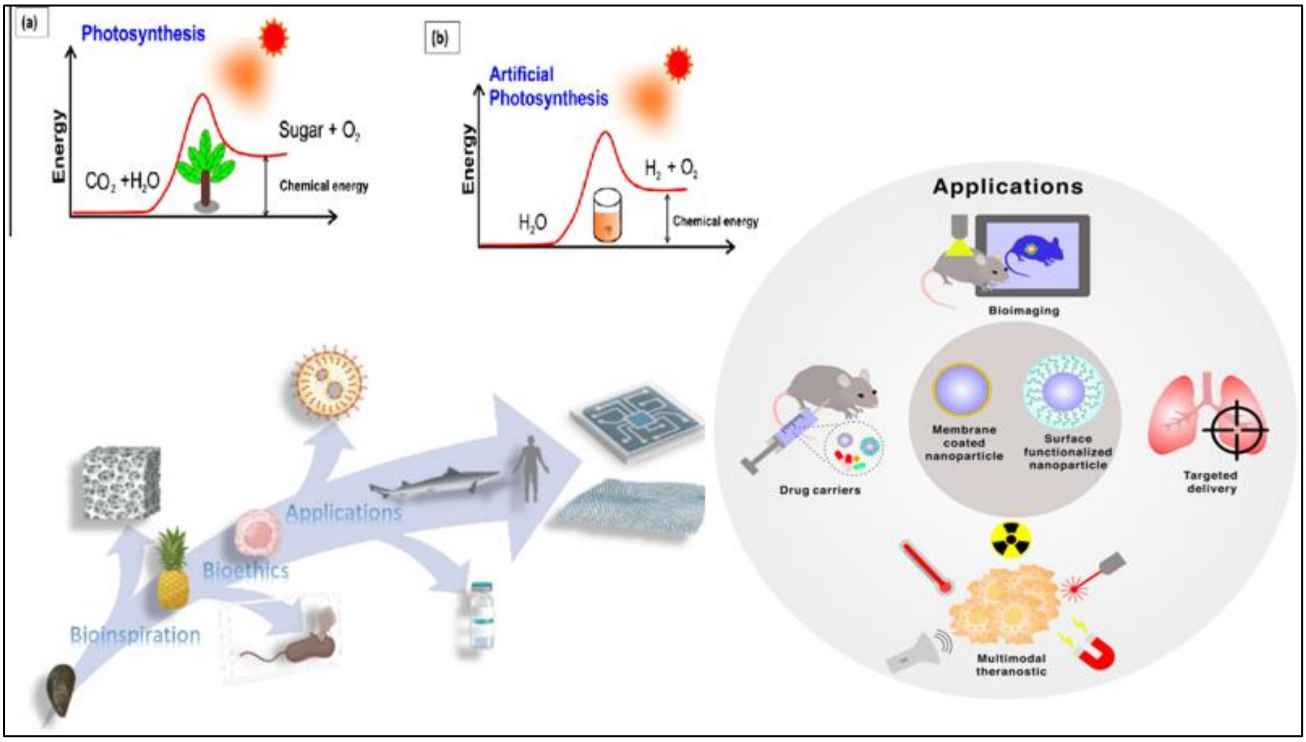



**Fig. 1: Bio-Inspired Nanotechnology Learning from Nature**

### Unveiling Ultra-Small Carbon Nanostructures

Ultra-small carbon nanostructures, particularly CDs with sizes below 2 nm, represent a groundbreaking frontier in nanotechnology due to their unique physicochemical properties (Ghasemlou *et al.*, 2024). Unlike their larger counterparts, these ultra-small CDs exhibit pronounced quantum confinement effects, significantly enhancing their optical, electronic, and chemical reactivity. This size-dependent behavior translates to exceptional photoluminescence, high photostability, and tunable emission spectra, making them prime candidates for bioimaging, drug delivery, and optoelectronics applications. However, synthesizing and characterizing CDs at such a diminutive scale pose formidable challenges (Akhter *et al.*, 2023). Precise control over size distribution, surface functionalization, and aggregation minimization are critical to exploiting their full potential. Compared to other carbon-based nanoparticles, such as fullerenes and carbon nanotubes, ultra-small CDs offer distinct advantages, including water solubility, lower cytotoxicity, and easier functionalization. Furthermore, their reduced size confers unique bio-reactivity, enabling efficient cellular uptake and interaction with biological systems without inducing significant adverse effects. Nevertheless, this enhanced reactivity raises concerns about potential long-term toxicity and environmental implications, necessitating comprehensive studies. By addressing these challenges, ultra-small CDs stand to surpass traditional nanoparticles, offering transformative opportunities in areas like quantum computing, biomedicine, and sustainable energy. Their integration into advanced technologies could redefine material science and open new avenues for innovation (Ninduwezuor-Ehiobu *et al.*, 2023).

### CDs in Artificial Intelligence and Data Storage

Carbon nanodots have emerged as key enablers in AI and advanced data storage technologies with their versatile photophysical properties and nano-scale dimensions (Litter *et al.*, 2023). In neuromorphic computing, CDs are being explored for their potential to mimic the brain's synaptic functionalities, facilitating bio-inspired memory devices. These devices aim to replicate the efficiency and adaptability of human neural networks, paving the way for energy-efficient AI systems capable of real-time learning and decision-making. CDs exhibit exceptional fluorescence stability, multicolor emission, and high photostability in high-density optical data storage, making them ideal for storing vast data in compact, durable formats (Yan *et al.*, 2023). Their tunable properties allow for precise control over data encoding, significantly enhancing storage density and retrieval speeds compared to traditional optical media. Furthermore, CDs are carving a niche in quantum cryptography, where their unique quantum confinement and electronic properties enable secure data transmission. Their role in developing quantum-resistant cryptographic keys could revolutionize data security, ensuring robust protection against cyber threats in an increasingly digitized world. These applications highlight CDs' transformative potential in bridging AI, advanced storage solutions, and secure information transfer, underscoring their importance in next-generation technological innovations (Lifelo *et al.*, 2024).

**Tackling the Invisible CDs in Air Quality Monitoring**

By using their unique optical and electrical characteristics to overcome the difficulties in identifying and reducing airborne pollutants, carbon dots (CDs) have become cutting-edge instruments in pollution management and air quality monitoring (Seesaard *et al.,* 2024). With CD-based sensors, which have strong chemical stability and adjustable fluorescence, detecting pollutants in real-time, such as $CO_2$, $NO_x$, and volatile organic compounds (VOCs), is now possible. These sensors are essential for monitoring urban air quality and prompt responses since they deliver fast and precise data. Additionally, CDs are used in sophisticated nano filters intended to be included in urban air cleaning systems (Mata *et al.,* 2022). These filters provide a scalable way to lessen urban pollution by effectively capturing and neutralizing dangerous gases and particles using CDs' catalytic and adsorptive qualities. Furthermore, wearable CD-powered air quality monitors represent a significant development in personal exposure monitoring. By giving people real-time feedback on air quality, these small, portable gadgets raise awareness and give users the tools they need to reduce their exposure to contaminants. In order to address the unseen issue of air pollution, CDs are transforming air quality management systems by fusing functionality, efficiency, and adaptability. This opens the door to cleaner surroundings and well-informed urban planning (Waddell *et al.,* 2002).

**Smart Carbon Nanodots in Adaptive Materials**

The fantastic optical, chemical, and electrical features of smart carbon nanodots (CDs) make them revolutionary agents in adaptive materials (Qureshi *et al.,* 2024). CDs in self-healing polymers improve the material's natural capacity to mend damage, resulting in long-term performance and endurance products. By reinforcing polymer networks and promoting effective energy transfer, these nanodots function as dynamic fillers or cross-linking agents, allowing materials to self-repair in response to environmental stimuli like light, heat, or pH variations. CDs are also essential to creating responsive coatings, providing corrosion and fog resistance features. Bright windows, wearable technology, and sophisticated optical displays benefit significantly from their optical tunability, enabling the development of color-changing surfaces that react to external stimuli. Furthermore, combining them with 4D printing technologies opens new material design possibilities, allowing for dynamic applications in which the printed structures may change and adapt over time (Ahmed *et al.,* 2021). These adaptable qualities, fueled by the combination of programmable polymers and CDs, open up new possibilities for applications in biomedical devices, aeronautical engineering, and soft robotics fields where accuracy, robustness, and responsiveness are crucial. Therefore, bright CDs are a crucial facilitator in the search for materials that can easily adjust to shifting conditions, bridging the gap between static and dynamically functioning materials (Chong *et al.,* 2002).

**Carbon Nanodots in Regenerative Medicine**

A revolutionary tool in regenerative medicine, carbon nanodots (or CDs) are a family of nanomaterials distinguished by their remarkable biocompatibility, easily functionalized surface, and adjustable fluorescence (Yi *et al.,* 2023). CDs are essential for differentiation and imaging in stem cell research. They are essential in regenerative treatments because of their capacity to modify the cellular milieu through functional surface groups, which promotes stem cell development into specific lineages. Furthermore, the inherent fluorescence of CDs makes it possible to see stem cell activities in real time, providing information on processes like migration, differentiation, and proliferation. CDs are included in scaffolds in tissue engineering to improve biocompatibility and offer extra features like antibacterial capabilities or the regulated release of bioactive compounds (Sharma *et al.,* 2021). These engineered scaffolds support cellular growth and guide tissue regeneration, allowing for simultaneous imaging and making them multifunctional platforms. Furthermore, CDs have shown promise as carriers in gene therapy, effectively delivering genetic material to target cells with high transfection efficiency and minimal cytotoxicity. This is mainly due to their small size, ease of conjugation with nucleic acids, and ability to bypass cellular barriers. Together, these properties position carbon nanodots as a versatile and potent tool in advancing regenerative medicine by enabling precise and multifaceted approaches to cellular therapy and tissue repair (Ibrahim *et al.,* 2023).

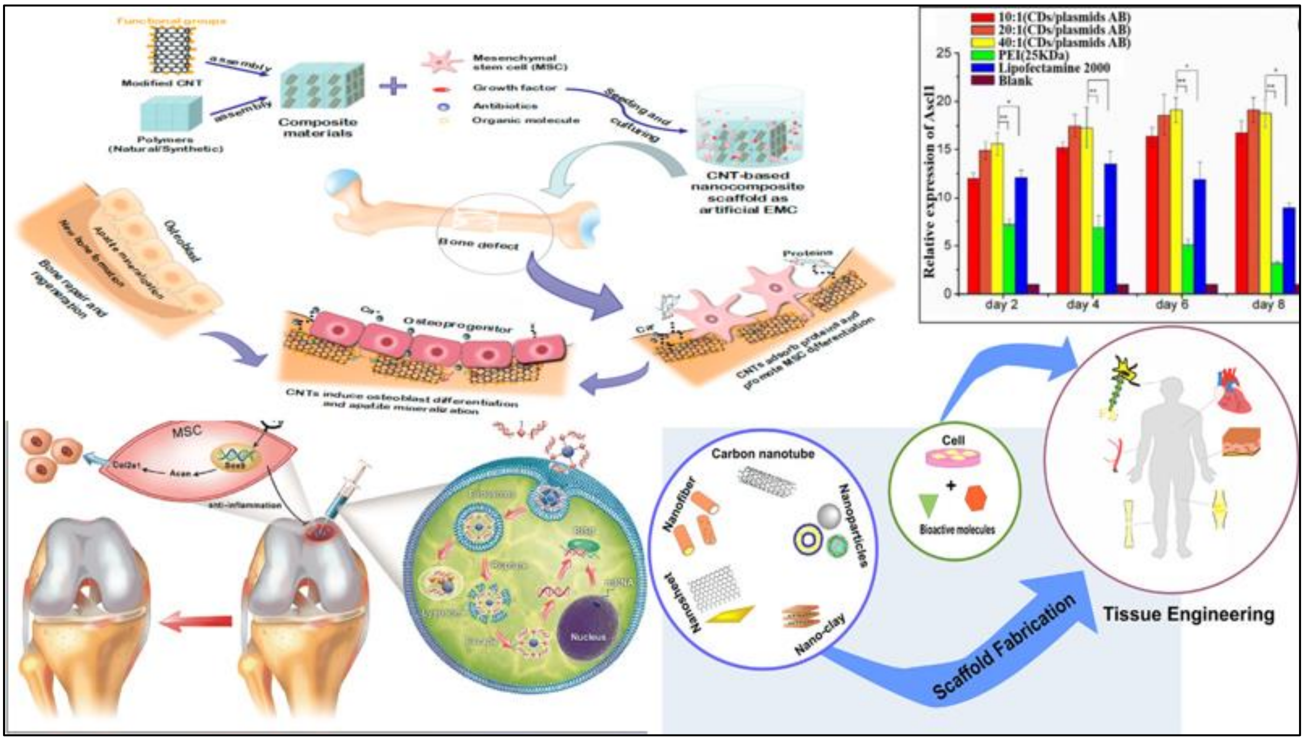



**Fig. 2: Carbon Nanodots in Regenerative Medicine**

### Space Age Applications of Carbon Nanodots

Because of their unique optical, chemical, and mechanical characteristics, carbon nanodots or CDs have become a material with a wide range of potential uses in the space era (Georgakilas *et al.,* 2015). Radiation shielding for extraterrestrial conditions is one of the most important applications for CDs. Astronauts and equipment are exposed to significant ionizing radiation during space exploration, especially solar radiation and cosmic rays. Because of their superior radiation-absorbing and converting properties, CDs may be used in flexible, lightweight shielding materials to provide increased protection without significantly increasing the weight of spacecraft (Gautam *et al.,* 2022). Furthermore, CDs have been successful in raising space-grade solar panels' efficiency. In the harsh space environment, where light intensity and angles fluctuate considerably, their superior photoluminescent qualities enable more effective solar energy conversion through increased light harvesting, broad-spectrum absorption, and enhanced charge transfer. CDs can also improve closed-loop life-support systems and space agriculture, critical for extended missions. Because of their catalytic and antibacterial qualities, CDs can enhance plant growth and nutrient absorption, which makes them perfect for preserving healthy crops in regulated settings. Additionally, CDs can contribute to water filtration and waste recycling, guaranteeing astronauts have sustainable life support systems. When taken as a whole, these properties make carbon nanodots essential in expanding the possibilities for space travel and settlement (Medina *et al.,* 2024).

### CDs in the Internet of Things (IoT)

In the IoT context, components such as communication devices that provide smooth data flow among interconnected ecosystems are called compact discs (Chakroun *et al.,* 2022). By gathering, analyzing, and sending data to enable real-time decision-making, these gadgets are essential to smart sensors, which are the foundation of the Internet of Things. For instance, CDs incorporated into high-efficiency, low-power communication devices use cutting-edge protocols like Bluetooth Low Energy (BLE), LoRa, or Zigbee to provide long-range connectivity with low power consumption, which makes them perfect for Internet of Things settings. Their use in smart cities is revolutionary. It allows energy management through smart grids and adaptive lighting systems while facilitating environmental monitoring through real-time weather tracking, water levels, and air quality (Mishra *et al.,* 2023). CDs facilitate the interoperability of many platforms and devices in these urban ecosystems, creating a unified network that boosts productivity. Their integration with AI-driven analytics also makes predictive insights possible, increasing IoT solutions' usefulness in lowering carbon footprints and maximizing resource use. CDs play a key role in developing IoT applications, especially in creating intelligent and sustainable urban settings, by tackling energy efficiency and secure communication (Gharaibeh *et al.,* 2017).

### CDs in the Food and Beverage Industries

Because of its many uses in improving safety, quality, and nutritional value, cyclodextrins (CDs) are transforming the food and beverage sectors (Matencio *et* *al.*, 2020). The creation of CD-based antimicrobial films for food packaging is one significant advance. By efficiently encasing antimicrobial compounds inside the CD cavity, these films provide a controlled release and ongoing defense against microbial development, increasing shelf life and decreasing food waste. Additionally, CDs are essential to colorimetric sensors that identify spoiling and freshness. CDs make Accurate food quality monitoring possible by enabling real-time visual changes in the sensor's color by forming inclusion complexes with volatile organic compounds (VOCs) or particular spoilage markers (Mazur *et al.*, 2024). Additionally, CDs serve as carriers for bioactive substances like vitamins, minerals, and antioxidants in nano-enabled food fortification. In addition to increasing the nutrients' stability and bioavailability, this encapsulation improves customer acceptability by covering up offensive flavors or smells. Because of their many uses, safety, and biodegradability, CDs are a key component of sustainable innovations in the food and beverage sectors, helping to solve important issues like waste reduction, food preservation, and the distribution of healthier, fortified products (Michel *et al.*, 2024).

**CDs for Advanced Military and Defense Applications**

Because of their unique optical, chemical, and physical characteristics, carbon dots have become a revolutionary material in cutting-edge military and defense applications (Singh *et al.*, 2024). CDs are essential to camouflaging systems in stealth technology because they allow for dynamic and adaptable concealment. They are perfect for making coatings or textiles that can replicate their surroundings by absorbing and emitting light at particular wavelengths. This renders military assets nearly invisible to optical and infrared imaging systems. Additionally, because CDs' surface functional groups enable quick and sensitive interaction with certain poisons or infections, they are being investigated for the real-time detection of chemical and biological warfare agents. These interactions, frequently indicated by the amplification or quenching of fluorescence, make it possible to create portable sensors that may be used in the field. CDs are also essential for portable energy storage systems designed for military-grade use (Atef *et al.*, 2022). They are ideal for supercapacitors and advanced batteries for harsh environments because of their large surface area, superior conductivity, and stability. These batteries provide faster charging times and increased energy density, essential for tactical operations, portable systems, and crewless aerial vehicles. The versatility of CDs, together with their low toxicity and compatibility with the environment, makes them an essential part of the next generation of military technology, propelling advancements in troop safety and defensive capabilities (Amiet *et al.*, 2010).

**Table 1: Applications of Carbon Dots (CDs) in Advanced Military and Defense Technologies**

| Application Area | Function of CDs | Key Advantages | Challenges & Limitations | Current Research & Future Prospects |
|---|---|---|---|---|
| **Tealth Technology for Camouflaging Systems** | CDs can be engineered to exhibit tunable fluorescence and near-infrared (NIR) emission, enabling dynamic and adaptive camouflage for military personnel and equipment. | High photostability- Tunable optical properties- Environmentally friendly alternatives to traditional stealth materials | Limited large-scale synthesis methods- Ensuring uniform dispersion of CDs on various surfaces | Development of multifunctional CD-based coatings for invisibility in different spectra- Integration with smart textiles and adaptive military uniforms |
| **Real-time Detection of Chemical and Biological Warfare Agents** | CDs serve as rapid-response fluorescent probes that can selectively detect toxic gases, nerve agents, and biological pathogens. | High sensitivity and selectivity, Fast response time, Portable and field-deployable sensor integration | Need for high specificity to reduce false positives, Stability in harsh battlefield conditions | Advances in functionalized CDs for multiplex detection of chemical and biological threats, Development of wearable CD-based sensors for soldiers |
| **Lightweight Energy Storage Devices for Military Applications** | CDs are used as electrode materials or additives in supercapacitors and lithium-ion batteries, improving energy density and charge-discharge cycles. | Lightweight alternative to conventional electrode materials, Enhanced conductivity and charge retention, Longer operational lifespan in extreme conditions | Balancing power density and energy density, Scalability for high-power applications | Research on hybrid CD-based nanocomposites for high-performance energy storage- Implementation in portable power sources for unmanned systems and wearable electronics |

| | | | | |
|---|---|---|---|---|
| **Thermal Imaging Countermeasures** | CDs can modify heat signatures, reducing detectability by infrared sensors and thermal imaging devices. | Effective at minimizing infrared signatures, Compatible with multiple surface coatings | Need for stable performance under diverse environmental conditions | Development of advanced CD composites for next-generation thermal camouflage |
| **Self-Healing Coatings for Military Equipment** | CDs incorporated in polymer matrices can enhance self-repair capabilities, reducing maintenance costs for vehicles and gear. | Improved durability and lifespan of coatings, Resistance to harsh environmental conditions | Optimization of mechanical strength while maintaining self-healing properties | Exploration of nanostructured CD-based materials for self-healing applications |
| **Advanced Optical Communication in Defense** | CDs serve as luminescent markers in optical communication systems for secure and efficient signal transmission. | High quantum yield, Wide emission range | Need for better signal amplification in real-world applications | Integration of CDs into quantum communication protocols for enhanced security |
| **Nanotherapeutics for Battlefield Medicine** | CDs can be functionalized for targeted drug delivery, aiding rapid wound healing and infection control in combat zones. | High biocompatibility-Potential for controlled drug release | Need for precise targeting and delivery efficiency | Development of CD-based antimicrobial and regenerative therapies for field medicine |

**Pioneering Carbon Nanodots in Cultural Heritage Preservation**

A groundbreaking class of carbon-based nanomaterials called carbon nanodots (or CDs) is significantly advancing in conserving and restoring cultural heritage (Abdelmonem *et al.*, 2025). Because of their unique optical, chemical, and antibacterial qualities, they are essential for noninvasive imaging and investigation of ancient artifacts. Excellent fluorescence on CDs allows for damage-free high-resolution photography of minute details in sculptures, paintings, and historical documents. This skill is essential for examining artifacts' structural soundness and composition, which offers information on the materials and methods used in their creation. Furthermore, CDs are essential in the fight against microbiological deterioration, which is one of the main dangers to old records and artwork (Cappitelli *et al.*, 2005). Their natural antibacterial qualities prevent bacteria and fungus from growing, preventing further degradation of fragile items, including paper, textiles, and wooden artifacts. Furthermore, by revitalizing deteriorated pigments in paintings and sculptures, CDs have created new opportunities in nano-restoration. The originality of the artwork may be maintained while restoring the brilliance of fading colors thanks to CDs' compatibility with a wide variety of organic and inorganic matrices. This innovative use not only improves visual attractiveness but also prolongs the life of cultural treasures. Collectively, using carbon nanodots represents a transformative approach to safeguarding cultural heritage for future generations (Ji *et al.*, 2023).

**CDs in Personalized Medicine and Health Tracking**

The unique qualities of CDs, such as their exceptional fluorescence, photostability, and biocompatibility, have made them a valuable tool in customized medicine and health tracking (Yao *et al.*, 2014). CDs are used in wearable biosensors for real-time glucose monitoring, providing diabetic patients with accurate and ongoing glucose level tracking. Better illness management and lifestyle modifications are made possible by incorporating CDs into lightweight, adaptable biosensing systems, which offer precise data with less invasiveness. Furthermore, CDs are making significant progress in liquid biopsies for early cancer diagnosis. Their great sensitivity makes it possible to identify trace amounts of tumor-derived biomarkers in blood or other body fluids, including exosomes and circulating tumor DNA (ctDNA). This non-invasive method improves early diagnosis and patient outcomes by enabling prompt treatments. Additionally, CDs are essential for monitoring patient healing with real-time biomarkers. They can be made to recognize specific molecular indicators of inflammation, tissue healing, or treatment effectiveness, giving doctors ongoing information on how well a patient is recovering. This further advances the idea of customized healthcare by allowing real-time modifications and personalization of treatment programs. The versatility of CDs in many applications highlights how revolutionary they may be in transforming personalized healthcare and patient monitoring.

**Revolutionary Environmental Sensors Using CDs**

The ultra-sensitive detection capabilities of carbon dots (CDs) nanodots make them innovative environmental sensors, especially when it comes to tracking microplastics in maritime environments (Rossetti *et al.*, 2015). These nanoscale carbon-based materials are perfect for detecting and measuring even minute levels of microplastics in marine settings because of their remarkable fluorescence characteristics, large surface area, and adjustable functionalization. Researchers are tackling the rising problem of plastic pollution in the oceans by creating extremely selective and quick detection techniques by utilizing CDs' optical and electrochemical characteristics. In addition to detecting microplastics, CDs are essential for tracking global warming indicators like carbon dioxide ($CO_2$) and methane ($CH_4$), which are significant causes of climate change (Wang *et al.*, 2024). To accurately measure emissions from industrial processes, agricultural sources, and natural reservoirs like wetlands and permafrost zones, functionalized CDs can be used as highly sensitive probes for real-time detection of these greenhouse gasses. Furthermore, aerial environmental surveillance is being revolutionized by incorporating CDs into drone-based systems, which enable high-resolution, large-scale monitoring of water and air pollutants. Policymakers and environmental scientists can receive real-time data from drones fitted with CD-based sensors, which can quickly scan large geographic areas and identify pollution concentrations. By combining remote sensing with nanotechnology, next-generation environmental monitoring systems are made possible, providing scalable, effective, and affordable answers to some of the most important ecological problems of the twenty-first century (Singh *et al.*, 2024).

**Table 2: Revolutionary Environmental Sensors Using Carbon Dots (CDs)**

| Category | Description | Advantages | Challenges | Future Directions |
|---|---|---|---|---|
| **Nanodots for Ultra-Sensitive Detection of Microplastics in Oceans** | Carbon dots (CDs) are integrated into sensors for detecting microplastics at nanomolar concentrations. They can distinguish polymer types based on fluorescence and surface interactions. | High sensitivity and selectivity, Cost-effective synthesis Fast detection compared to traditional methods Can be embedded in portable sensors | Stability in marine environments, Potential bioaccumulation concerns Need for scalable fabrication | Development of real-time monitoring systems Hybrid nanocomposite sensors for enhanced detection, Integration with AI for automated data analysis |
| **Role in Monitoring Global Warming Indicators (Methane & CO2 Levels)** | CDs are functionalized with specific receptors to detect methane (CH4) and carbon dioxide (CO2) in the atmosphere. These sensors exhibit fluorescence quenching or enhancement upon gas binding, enabling precise monitoring. | High sensitivity to low gas concentrations, Energy-efficient monitoring Miniaturization for portable use Remote sensing capability | Calibration for diverse environmental conditions, Interference from other atmospheric gases Durability and lifespan of sensors | Smart grids for real-time climate monitoring Internet of Things (IoT) integration for automated sensing - AI-driven predictive modeling using sensor data |
| **Integrating CDs in Drones for Aerial Environmental Surveillance** | CDs-based sensors are embedded in drones for large-scale environmental monitoring. They provide data on pollutants, greenhouse gases, and water quality. | Wide-area coverage - Rapid data collection Reduced human intervention Ability to reach inaccessible regions | Power consumption limitations, and Interference from environmental variables Data transmission security risks | Swarm drone technology for synchronized monitoring AI-enhanced drone navigation for efficient data collection Advanced multi-spectral analysis for comprehensive environmental assessment |

| | | | | |
|---|---|---|---|---|
| **Detection of Heavy Metals in Water** | CDs functionalized with chelating agents detect heavy metals ($Pb^{2+}$, $Hg^{2+}$, $Cd^{2+}$) in water bodies, exhibiting fluorescence shifts upon binding. | Ultra-low detection limits, Real-time water quality assessment Cost-effective deployment | Sensor longevity in harsh environments, Need for multi-ion selectivity, Field validation with existing monitoring systems | Smart filtration systems coupled with detection Multi-target sensing platforms, Portable and wearable water-quality testing devices |
| **Air Quality Monitoring for Industrial Pollution** | CDs are incorporated into sensors to measure airborne particulate matter (PM2.5, PM10) and volatile organic compounds (VOCs). | High spatial resolution of pollutants Low-cost fabrication Fast response time, Potential for real-time urban pollution mapping | Sensitivity to humidity and temperature variations, Maintenance of long-term sensor performance, Standardization of CD-based sensors | Smart city integration for automated pollution control - AI-driven emission source tracking - Advanced sensor arrays for multi-pollutant detection |
| **Soil Contamination Assessment** | CDs-based probes detect pesticides, fertilizers, and heavy metal contamination in agricultural fields. | Rapid soil health evaluation, Reduced need for labor-intensive testing Potential for precision agriculture applications | Stability of CDs in different soil types, Effectiveness in complex soil matrices, Standardization of detection protocols | Smart farming applications IoT-based soil health monitoring, Development of biodegradable CDs for eco-friendly use |
| **Oil Spill Detection in Water Bodies** | CDs functionalized with hydrophobic moieties detect oil contamination through fluorescence-based imaging techniques. | High contrast detection, Portable application for field assessments, Real-time monitoring capability | Sensitivity to environmental interferences, Efficiency in different water salinities, Recovery and reusability of sensors | AI-assisted image recognition for rapid spill identification Drone-based real-time oil spill mapping Integration with bioremediation techniques |
| **Smart Packaging for Food Safety** | CDs are embedded into food packaging materials to detect spoilage gases (e.g., ammonia, hydrogen sulfide). | Non-invasive food safety monitoring - Early detection of spoilage, Extension of shelf life | Regulatory approvals for food-grade safety, Sensitivity variations across food types, Scalability of manufacturing | Integration with smartphone apps for consumer safety AI-driven analytics for supply chain monitoring Sustainable and biodegradable sensor materials |

## CONCLUSION

A revolutionary advancement in nanotechnology, the confluence of basic research and commercial applications in the field of carbon dots (CDs) has the potential to completely overhaul a variety of sectors, including environmental science and medicine. The difficulty is in converting these discoveries into scalable, affordable, and economically viable technologies, even if laboratory-scale developments have shown CDs' unique optical, electrical, and biocompatible qualities. To close this gap, industry, academia, and regulatory agencies must work together to improve repeatability, refine synthesis techniques, and guarantee safety for extensive use. With its incorporation into bioimaging, medication delivery, photovoltaics, and environmental remediation providing affordable and sustainable substitutes for traditional materials, CDs are expected to have a significant societal and economic effect. The potential of CDs as non-toxic drug carriers and imaging agents, which lessen dependency on conventional dyes and heavy-metal-based quantum dots, is especially advantageous for the biomedical industry. Demand for CDs has increased because their use in next-generation energy storage devices and water purification systems complies with international sustainability standards. However, resolving scaling issues, regulatory obstacles, and customer acceptability are necessary for economic viability. The broad use of CDs will probably spur innovation in various fields as research into their characteristics and capabilities continues, ushering in a new era of nanomaterial-driven solutions with significant societal and financial ramifications.

## REFERENCES


- Abdelmonem, M., Nair, R. D., Ibrahim, M. A., Soomro, R., Meli, A. D., Pratiwi, A. R., ... & Che Abdullah, C. A. (2025). Synthesis and Characterization of Agricultural Waste-Derived Carbon Nanomaterials (AWD-CNMs) for Tissue Engineering Applications. In *Waste-Derived Carbon Nanostructures: Synthesis and Applications* (pp. 233-270). Cham: Springer Nature Switzerland.
- Ahmed, A., Arya, S., Gupta, V., Furukawa, H., & Khosla, A. (2021). 4D printing: Fundamentals, materials, applications, and challenges. *Polymer*, *228*, 123926.
- Akhter, F., Ahmed, J., Pinjaro, M. A., Shaikh, F. A., Arain, H. J., & Ahsan, M. J. (2023). Metal-doped carbon dots (MCDs) as efficient nano-adsorbents for detecting, monitoring, and degrading wastewater pollutants: recent progress, challenges, and prospects. *Water, Air, & Soil Pollution*, *234*(11), 672.
- Amiet, A. R., Edwards, D. P., Ibrahim, M. E., Mart, P. L., McAdam, G., St John, N. A., & Truong, V. T. (2010). Exploitation of Smart Materials and Sensors as Disruptive Technologies.
- Ashbourn, J. (2020). Audio technology, music, and media. *Cham, Switzerland: Springer Nature. Doi*, *10*, 978-3.
- Atef, A., Omar Alif, K. M., Ahmed, J., Rupak, B. H., & Tasnim, M. (2022). Foldable and portable solar module-based energy generation system to meet communication sector power demand in military remote camps.
- Bellman, J. D. (2020). Billy Joel, Piano Culture, and Rock’s Road not Taken. *" We Did Not Start the Fire": Billy Joel and Popular Music Studies*, 49.
- Byers, F. R. (2003). Care and Handling of CDs and DVDs—A Guide for Librarians and Archivists. *NIST Special Publication*, *500*(252), 1-40.
- Cappitelli, F., & Sorlini, C. (2005). From papyrus to compact disc: the microbial deterioration of documentary heritage. *Critical reviews in microbiology*, *31*(1), 1-10.
- Carriere, J., Yeh, W. H., Peng, C., Khulbe, P., Li, L., Choi, J., ... & Anderson, R. (2000). Principles of optical disk data storage. In *Progress in Optics* (Vol. 41, pp. 97-179). Elsevier.
- Chakroun, M., Sayah, J., Kallab, C., & Haddad, S. (2022). Internet of Things: Towards a solid ecosystem of interconnected things. *Advances in Internet of Things*, *12*(3), 35-64.
- Chen, B. B., Liu, M. L., Li, C. M., & Huang, C. Z. (2019). Fluorescent carbon dots functionalization. *Advances in colloid and interface science*, *270*, 165-190.
- Chong, K. P., & Garboczi, E. J. (2002). Innovative and designer structural material systems. *Progress in Structural Engineering and Materials*, *4*(4), 417-430.
- Dutta, V., Verma, R., Gopalakrishnan, C., Yuan, M. H., Batoo, K. M., Jayavel, R., ... & Ghotekar, S. (2022). Bio-inspired synthesis of carbon-based nanomaterials and their potential environmental applications: a state-of-the-art review. *Inorganics*, *10*(10), 169.
- Gautam, Y. K., Sharma, K., Tyagi, S., Kumar, A., & Singh, B. P. (2022). Applications of green nanomaterials in coatings. In *Green Nanomaterials for Industrial Applications* (pp. 107-152). Elsevier.
- Georgakilas, V., Perman, J. A., Tucek, J., & Zboril, R. (2015). A broad family of carbon nano allotropes: classification, chemistry, and applications of fullerenes, carbon dots, nanotubes, graphene, nanodiamonds, and combined superstructures. *Chemical Reviews*, *115*(11), 4744-4822.
- Georgakilas, V., Perman, J. A., Tucek, J., & Zboril, R. (2015). Broad family of carbon nano allotropes: classification, chemistry, and applications of fullerenes, carbon dots, nanotubes, graphene, nanodiamonds, and combined superstructures. *Chemical Reviews*, *115*(11), 4744-4822.
- Gharaibeh, A., Salahuddin, M. A., Hussini, S. J., Khreishah, A., Khalil, I., Guizani, M., & Al-Fuqaha, A. (2017). Smart cities: A survey on data management, security, and enabling technologies. *IEEE Communications Surveys & Tutorials*, *19*(4), 2456-2501.
- Ghasemlou, M., Pn, N., Alexander, K., Zavabeti, A., Sherrell, P. C., Ivanova, E. P., ... & Bhargava, S. K. (2024). Fluorescent Nanocarbons: From Synthesis and Structure to Cancer Imaging and Therapy. *Advanced Materials*, *36*(19), 2312474.
- Hachiya, M. (2010). *Historical Review of Sony's Innovations and Future Steps* (Doctoral dissertation, Massachusetts Institute of Technology).
- Ibrahim, I., Ayariga, J., Xu, J., Robertson, B. K., & Ajayi, O. (2023). Exploring the Synergy of Carbon Nanodots in Enhancing Cannabidiol Delivery and Therapeutic Efficacy: A Comprehensive Review.
- Idoko, F. A., Ezeamii, G. C., & Ojochogwu, O. J. (2024). Green chemistry in manufacturing: Innovations in reducing environmental impact. *World Journal of Advanced Research and Reviews*, *23*(3), 2826-2841.
- Ji, D. K., Zhang, R., & Bianco, A. (2023). Engineered DNA-copper double-modified NIR carbon nanodots as oxidative stress amplifier for targeted intracellular production of reactive oxygen species: carbon, *214*, 118369.
- Kar, S., Sanderson, H., Roy, K., Benfenati, E., & Leszczynski, J. (2021). Green chemistry in the synthesis of pharmaceuticals. *Chemical Reviews*, *122*(3), 3637-3710.

- Lifelo, Z., Ding, J., Ning, H., & Dhelim, S. (2024). Artificial Intelligence-Enabled Metaverse for Sustainable Smart Cities: Technologies, Applications, Challenges, and Future Directions. *Electronics*, *13*(24), 4874.
- Litter, M. I., & Ahmad, A. (2023). *Industrial Applications of Nanoparticles*. CRC Press: Boca Raton, FL, USA.
- Liu, M. L., Chen, B. B., Li, C. M., & Huang, C. Z. (2019). Carbon dots: synthesis, formation mechanism, fluorescence origin, and sensing applications. *Green chemistry*, *21*(3), 449-471.
- Liu, S., Xu, Y., Wang, X., Zhou, H., & Zhang, T. (2024). Insight into the synthetic strategies of carbon dots and its Structure-Property interplay for Next-Generation technologies. *Chemical Engineering Journal*, *496*, 153914.
- Liu, Y., Huang, H., Cao, W., Mao, B., Liu, Y., & Kang, Z. (2020). Advances in carbon dots: from the perspective of traditional quantum dots. *Materials Chemistry Frontiers*, *4*(6), 1586-1613.
- Mata, T. M., Martins, A. A., Calheiros, C. S., Villanueva, F., Alonso-Cuevilla, N. P., Gabriel, M. F., & Silva, G. V. (2022). Indoor air quality: a review of cleaning technologies. *Environments*, *9*(9), 118.
- Matencio, A., Navarro-Orcajada, S., García-Carmona, F., & López-Nicolás, J. M. (2020). Applications of cyclodextrins in food science. A review. *Trends in food science & technology*, *104*, 132-143.
- Mazur, F., Han, Z., Tjandra, A. D., & Chandrawati, R. (2024). Digitalization of colorimetric sensor technologies for food safety. *Advanced Materials*, *36*(42), 2404274.
- MEDINA, R. A., FRANCO, M. E., DE JUAN-CORPUZ, L. M., & CORPUZ, R. D. (2024). Photoluminescent carbon nanodots for artificial photosynthesis. *Journal of Metals, Materials and Minerals*, *34*(1), 1824-1824.
- Michel, M., Eldridge, A. L., Hartmann, C., Klassen, P., Ingram, J., & Meijer, G. W. (2024). Benefits and challenges of food processing in the context of food systems, value chains, and sustainable development goals. *Trends in Food Science & Technology*, 104703.
- Mishra, P., & Singh, G. (2023). Energy management systems in sustainable smart cities based on the internet of energy: A technical review. *Energies*, *16*(19), 6903.
- Mishra, R. K., Chianella, I., Sarkar, J., Yazdani Nezhad, H., & Goel, S. (2024). Nanostructured ZnO-CQD Hybrid Heterostructure Nanocomposites: Synergistic Engineering for Sustainable Design, Functional Properties, and High-Performance Applications. *ChemNanoMat*, *10*(7), e202400020.
- Ninduwezuor-Ehiobu, N., Tula, O. A., Daraojimba, C., Ofonagoro, K. A., Ogunjobi, O. A., Gidiagba, J. O., ... & Banso, A. A. (2023). Exploring innovative material integration in modern manufacturing to advance competitiveness in the sustainable global economy. *Engineering Science & Technology Journal*, *4*(3), 140-168.
- Qureshi, Z. A., Dabash, H., Ponnamma, D., & Abbas, M. K. G. (2024). Carbon dots as versatile nanomaterials in sensing and imaging: Efficiency and beyond. *Heliyon*, *10*(11).
- Rossetti, M., Porchetta, A., Petropoulos, K., Ricci, F., Micheli, L., Volpe, G., & Palleschi, G. (2015). SENSING TOXICANTS IN MARINE WATERS MAKES SENSE USING BIOSENSORS. In *GS 2015* (pp. 59-59). IT.
- Rothenbuhler, E. W. (2012). The compact disc and its culture: Notes on melancholia. *Cultural Technologies*, 36-50.
- Seesaard, T., Kamjornkittikoon, K., & Wongchoosuk, C. (2024). A comprehensive review of advancements in sensors for air pollution applications. *Science of The Total Environment*, 175696.
- Sharma, S., Sudhakara, P., Singh, J., Ilyas, R. A., Asyraf, M. R. M., & Razman, M. R. (2021). A critical review of biodegradable and bioactive polymer composites for bone tissue engineering and drug delivery applications. *Polymers*, *13*(16), 2623.
- Sheldon, R. A. (2017). The E factor 25 years on: the rise of green chemistry and sustainability. *Green Chemistry*, *19*(1), 18-43.
- Singh, N. B., Kumar, B., Usman, U. L., & Susan, M. A. B. H. (2024). Nano revolution: Exploring the frontiers of nanomaterials in science, technology, and society. *Nano-Structures & Nano-Objects*, *39*, 101299.


- Singh, N. B., Kumar, B., Usman, U. L., & Susan, M. A. B. H. (2024). Nano revolution: Exploring the frontiers of nanomaterials in science, technology, and society. *Nano-Structures & Nano-Objects*, *39*, 101299.


- Sonowal, L., & Gautam, S. (2024). Advancements and challenges in carbon nanotube-based drug delivery systems. *Nano-Structures & Nano-Objects*, *38*, 101117.
- Tariq, S. (2024). Breaking Boundaries: How Multidisciplinary Research Fuels Innovation Across Fields. *Physical Education, Health and Social Sciences*, *2*(03), 15-28.
- Thomas, J. M. (2014). Heterogeneous catalysis and the challenges of powering the planet, securing chemicals for civilized life, and efficiently utilizing renewable feedstocks. *ChemSusChem*, *7*(7), 1801-1832.
- Waddell, P. (2002). UrbanSim: Modeling urban development for land use, transportation, and environmental planning. *Journal of the American Planning Association*, *68*(3), 297-314.
- Wang, Y., Zhao, C., Lu, A., Dong, D., & Gong, W. (2024). Unveiling the hidden impact: How

biodegradable microplastics influence CO2 and CH4 emissions and Volatile Organic Compounds (VOCs) profiles in soil ecosystems—Journal *of Hazardous Materials*, *471*, 134294.

- Yan, Z., Hu, J., Xiao, Z., Xie, D., Cao, Q., Gan, Z., & Zhang, J. (2023). Decoding the future: Opportunities and challenges in next-generation optical data storage. *Chinese Optics Letters*, *21*(12), 120051.
- Yang, J., Liu, Y., Liu, S., Li, L., Zhang, C., & Liu, T. (2017). Conducting polymer composites: material synthesis and applications in electrochemical capacitive energy storage. *Materials Chemistry Frontiers*, *1*(2), 251-268.
- Yao, J., Yang, M., & Duan, Y. (2014). Chemistry, biology, and medicine of fluorescent nanomaterials and related systems: new insights into biosensing, bioimaging, genomics, diagnostics, and therapy. *Chemical Reviews*, *114*(12), 6130-6178.
- Yi, W., Khalid, A., Arshad, N., Asghar, M. S., Irshad, M. S., Wang, X., ... & Li, H. R. (2023). Recent Progress and Perspective of an Evolving Carbon Family From 0D to 3D: Synthesis, Biomedical Applications, and Potential Challenges. *ACS Applied Bio Materials*, *6*(6), 2043-2088.
- Zhou, Y., Zhang, W., & Leblanc, R. M. (2022). Structure-property–activity relationships in carbon dots. *The Journal of Physical Chemistry B*, *126*(51), 10777-10796.
- Zhou, Y., Zhang, W., & Leblanc, R. M. (2022). Structure-property–activity relationships in carbon dots. *The Journal of Physical Chemistry B*, *126*(51), 10777-10796.
- Zhu, L. T., Chen, X. Z., Ouyang, B., Yan, W. C., Lei, H., Chen, Z., & Luo, Z. H. (2022). Review of machine learning for hydrodynamics, transport, and reactions in multiphase flows and reactors. *Industrial & Engineering Chemistry Research*, *61*(28), 9901-9949.
- Harun-Ur-Rashid, M., Jahan, I., Foyez, T., & Imran, A. B. (2023). Bio-inspired nanomaterials for micro/nanodevices: a new era in biomedical applications. *Micromachines*, *14*(9), 1786.