EMERGING NANOMATERIALS IN SUSTAINABLE ENERGY SYSTEMS

Editor:
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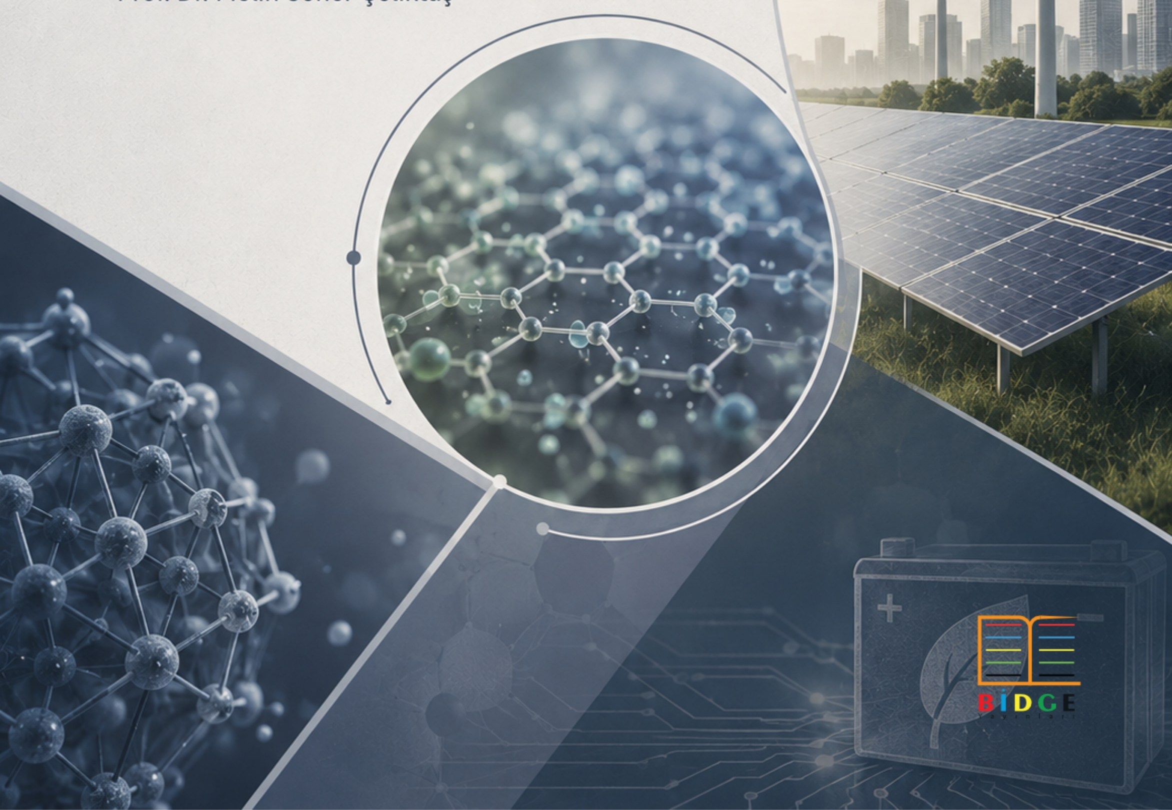

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CHAPTER 1

NANOCOMPOSITE SYSTEMS FOR PHOTOVOLTAIC CELLS

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1.Introduction

The global community has focused a lot of attention on solar energy as a potential renewable resource in the search for an alternative energy source because of its endless supply and ecologically favourable qualities, which could help address the problem of global warming and the depletion of fossil fuels (Appasamy et al., 2020). Solar energy, the most plentiful and promising renewable energy source, has the potential to provide all of the world's energy demands (Mersin & Çeliktaş, 2023). Researchers are focusing more on renewable energy sources

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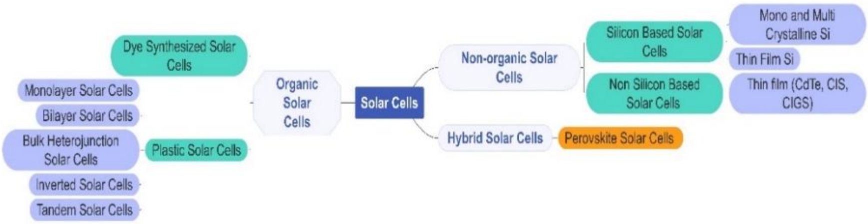
(Ozliman & Celiktas, 2025) particularly solar energy, which is a clean, abundant source of energy, due to the scarcity of conventional energy sources like fossil fuels and their possibly detrimental consequences on the environment. Therefore, researchers must employ a range of solar energy conversion systems and technologies to convert the absorbed solar radiation into usable heat and power in addition to producing solar collector systems like flat-plate collectors that collect solar radiation (Al-Ali et al., 2025). Photovoltaic Cells (PV) gets transformed by photovoltaic panels into electrical energy (Deniz & Çeliktaş, 2023). The surface temperature of the solar cells is frequently influenced by common environmental elements, including ambient temperature, wind speed, dust, and sun irradiation. Numerous studies have been conducted on the influence of these characteristics on PV module performance. It is well known that when temperatures rise, solar PV cell efficiency falls, necessitating the use of cooling in situations with intense illumination or high temperatures (Hachim et al., 2021).

The four primary classes of developed solar cell technology, referred to as generations, are as follows: The first generation involved silicon (*Si*) wafers, both polycrystalline and monocrystalline, as well as gallium arsenide (*GaAs*); the second generation involved thin films based on amorphous Si, cadmium telluride (*CdTe*), copper indium gallium and selenium (*CIGS*), and cooper zinc tin sulphide solar cells (*CZTS*); the third generation included organic and polymeric solar cells, dye-sensitized solar cells (*DSSC*), quantum dot solar cells, perovskite solar cells (C. Wu et al., 2020), etc.; and the fourth generation, referred to as "inorganic-in-organic" generation (Socol & Preda, 2021). Figure 1 shows the primary classes of solar cell technology.

Figure 1. The primary classes of solar cell technology (Patel et al., 2014).



The urgent need for sustainable energy has encouraged extensive research into different types of solar cells to reduce reliance on fossil fuels and restrain environmental damage. Because of that over the past fifty years, research has research has concentrated on finding eco-friendly materials and reducing processing costs for photovoltaic systems (Celiktas & Kocar, 2010).

PV cells have some challenges to improve their efficiency and cost-effectiveness. The challenges should be overcome to enhance efficiency of PV cells. Cleaning is known as one of the challenges that PV cells faced (Aljaghoub et al., 2022; Garip et al., 2022; Huang, 2021; Salamah et al., 2022). The accumulation of dirt on solar panel surfaces because of inclement weather, urban pollution, bird droppings, and microbial poses a substantial barrier to the widespread application of solar energy (T. W. Chen et al., 2020; Najmi & Rachid, 2023; Uysal & Çeliktaş, 2023). Dirt accumulation would make it more difficult for sunlight to reach the surface, decreasing the solar PV cells' effectiveness (Adekanbi et al., 2024; Appasamy et al., 2020). Hence, regular cleaning of PV cells is necessary for improving solar cells' effectiveness. To accomplish capabilities required in solar cells but not achievable with a single material, elements with varied properties are mixed in nanocomposites. The use of highly absorbent materials with extremely low drift or diffusion lengths of photogenerated charge carriers in solar cells was made possible by nanocomposite absorbers (H. Zhang et al., 2025).

There are worldwide efforts to create efficient and lightweight equipment, particularly for generating electricity with photovoltaic (PV) cells (Birtürk & Celiktas, 2024). This necessitates research into advanced engineering methods that replace metals and alloys, resulting in superior mechanical properties and reduced weight (Olorunfemi et al., 2022).

Nanotechnology focuses on fabricating materials and particles at the nanoscale. These substances, called nanoparticles and nanomaterials, possess unique qualities that are absent in bulk materials, and these materials are between one and one hundred nanometers, granting unique properties for specific purposes. At the nanoscale, materials exhibit distinct characteristics from bulk matter or individual atoms, leading to new applications. Nanocomposites, containing nanoscale additions in one phase (Alptekin et al., 2023; Altammar, 2023; Babick et al., 2016; Celiktas & Alptekin, 2019), enhance mechanical, thermal, chemical, and electrical properties significantly (Al-Mutairi et al., 2022). Nanotechnology involves manipulating molecular structures to assemble precise systems of atoms by atom. Examples include metal oxides, quantum dots, silicon dioxide, dendrimers, and layered structures (W. S. Khan et al., 2022).

A nanocomposite is, on the other hand, a matrix or combination of materials that creates new properties while guaranteeing that at least one of the materials has a size between one and one hundred nanometers. Because of their superior qualities over single metal nanoparticles, scientists have recently become quite interested in and attentive to nanocomposites materials (Gemachu & Bogale, 2024). Ongoing investigation to enhance material properties through modifications to reaction parameters, composite formation, post-treatment, and other structural design elements (Elemike et al., 2022).

In this chapter, the use of nanocomposites in PV systems is discussed in order to overcome the disadvantages of PV systems and increase their efficiency. First, the fundamentals of nanocomposite materials are presented, and the role of nanocomposites in improving photovoltaic performance, sustainability assessment of nanocomposite technologies and the future of nanocomposite technologies in the solar energy sector are examined under separate headings. Finally, it is concluded by presenting the developments and applications in the use of nanocomposite technologies in PV.

2. Basics of Nanocomposite Materials

Two or more components are combined to create composites. They provide a wide range of applications when they are produced by mixing different functional group materials with their improved qualities (Navidfar & Trabzon, 2026). Materials known as nanocomposites are heterogeneous or hybrid materials produced by combining nanoscale particles from regular materials with specific combinations of properties. Complex structures can be found within nanocomposites. The content, structure, and interfacial interactions of each individual component will determine the overall structure of the nanocomposites. Solid structures known nanocomposites are created by adding nanosized particles—0.5–5% by weight—to a normal material matrix (Patil, 2021). The main benefits of nanocomposites above other types of composite materials are their outstanding mechanical qualities, such as their high elasticity without losing strength and scratch resistance, and their high surface/volume ratio, which permits small filler sizes and spacing between fillers. enhanced optical qualities (Aljaghoub et al., 2022; Celiktas et al., 2021; Gemachu & Bogale, 2024). Physical, mechanical, electrical, optical, chemical, and magnetic properties are possessed by nanocomposites. By modifying their internal buildings, they can be manufactured from any traditional material, including ceramics, metals and alloys, and polymers. Liquid metallurgy, solid state processing methods, and other fundamental science synthesis pathways can all be used to create nanocomposites (Khumalo & Khoathane, 2021).

Two classes are commonly used to categorize the synthesis techniques of nanocomposites. Both top-down and bottom-up methods are used here (El-Khawaga et al., 2023). The process of creating materials from molecules to groupings to nanoparticles is known as the bottom-up or constructive approach. The most popular bottom-up techniques for creating nanoparticles include sol-gel, spinning, chemical vapour deposition, pyrolysis, and biosynthesis (Celiktas et al., 2014; Ilhan-Ayisigi et al., 2021). The top-down method creates nanoparticles by reducing their size, which separates them into tiny particles from the bulk material (S. Ahmed et al., 2016; Yesil-Celiktas et al., 2013).

The accurate characterization of nanoparticles presents a variety of challenges, and selecting an effective approach is critical. Nanoparticle characterization determines the surface area, porosity, solubility, particle size distribution, aggregation, hydrated surface analysis, zeta potential, wettability, adsorption potential, shape, size of the interactive surface, crystallinity, fractal dimensions, orientation, intercalation, and dispersion of nanoparticles and nanotubes in nanocomposite materials (Jagadeesh et al., 2024; Nivetha et al., 2025). To effectively evaluate the structural properties of the nanocomposites, it is important to characterize their structural morphology. To find out more about the shape, particle size, phase, composition, thermal stability, optical, magnetic, electrical, and thermal properties of the produced nanocomposites, various techniques can be used to characterize them. X-ray diffraction analysis (X-RD), Fourier transform infrared spectroscopy

(FTIR), ultraviolet visible light spectroscopy (UV-Vis), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and thermal analysis (TA) are a few of the frequently used methods (Gemachu & Bogale, 2024). Together with these, Field Emission Scanning Electron Microscopy (FESEM) is used to characterize the nanocomposite (Appasamy et al., 2020).

According to the types of matrixes and strengthening substances used in their manufacture, nanocomposites are categorized. The classification of nanocomposites is based on the material of the matrix: metal matrix nanocomposites (MMNC), polymer matrix nanocomposites (PMNC), and ceramic matrix nanocomposites (CMNC) (Gemachu & Bogale, 2024). The mechanical, electrochemical, electrical, catalytic, thermal, and optical characteristics of the nanocomposites can vary significantly from those of the component materials, or they can combine. The phases of the nanocomposites are as follows: zero-dimensional (core shell) (S. Chen et al., 2020), one-dimensional (nanowires and nanotubes) (Abraham, 2021), two-dimensional (lamellar) (Pan et al., 2022), and three-dimensional (metal matrix composites) (Gemachu & Bogale, 2024).

2.1. Types of nanocomposite structures (e.g., polymer-based, metal-based, semiconductor-based)

To provide an overview of nanocomposites, it is necessary to look at nanocomposite structures. Nanocomposites are structurally evaluated in five main categories.

2.1.1. Polymer-based

Polymer matrix nanocomposites (PNCs) are the most popular kind of nanocomposite. They are composed of up of isolated nanoscale particles that are uniformly dispersed throughout a polymer under ideal conditions (Al-Mutairi et al., 2022). Because of the characteristics of their combined structure that none of the components of PNCs can equal, polymeric nanocomposites hold great promise for a wide range of prospective applications. The mechanical, thermal, and electrical properties of the polymer might all be greatly enhanced (J.-W. Li et al., 2024). PNCs can be fabricated into the appropriate sizes and forms. PNCs' low cost and light weight have also enhanced their potential usage in several industrial and environmental applications.

There are two kinds of polymers: synthetic and natural. Natural polymers are those that can be extracted for usage from their natural habitat (Getahun et al., 2024). Water is a common constituent of natural polymers, including cellulose, silk, wool, and proteins. Several factors, including the polymeric system being utilized, the intended application field, particle dispersion, size, etc., influence the preparation technique selection (Shabbir & Luo, 2021). In zero-dimensional (0D) nanocomposites, all three filler dimensions—spherical silicate nanoparticles, metal and metal oxide nanoparticles, detonation nanodiamonds, quantum dots, etc.—are about 1 nm. One-dimensional (1D) nanocomposites consist of a filler that is nanosized in two dimensions (nanotubes, fibers, or whiskers), whereas two-dimensional (2D) nanocomposites are layers with a nanoscale thickness (layered silicates, metal chalcogenidies, graphite, etc.) (S. Khalid et al., 2025). Two examples of carbon nanotube-polymer nanocomposites include clay-polymer nanocomposites. One-dimensional nano additions include nanotubes and fibers; two-dimensional additives include layered materials like clay; and three-dimensional additives include spherical particles (Venkatesan et al., 2021).

2.1.2. Metal-based

Like other composites, metal matrix composites (MMCs) consist of a minimum of two physically and chemically distinct phases that are are dispersed to give characteristics that neither of the individual phases can provide (Al-Mutairi et al., 2022). These composites, which are made of a metal/alloy matrix finished with nanoparticles, have entirely distinct mechanical, chemical, and physical characteristics from the matrix material (Sarode et al., 2023). These nanocomposites consequently are ideal to generate materials with high shear/compression strengths and high service temperatures. They hold great potential for usage in many other fields, such as the manufacturing of structural materials and the automotive and aerospace sectors (M. Y. Khalid et al., 2023). As a case study, metal oxides such as titanium dioxide (TiO2), zinc oxide (ZnO), and nickel oxide (NiO) have outstanding electron mobility and acceptable visual properties. These materials can be used in solar cells as electron or hole carrier layers, UV protection, and light scattering (Etefa & Kumar, 2023).

2.1.3. Ceramic-based

Ceramics are a material type that has seen a lot of application due to their structural significance in terms of resistance to chemicals, high pressure and temperature, and wear (Ni et al., 2022). Since their discovery, these materials have been employed in a plethora of industrial applications, involving mining equipment, combustion engines, nuclear power plants, and spacecraft. The oxides (silica, alumina, and zirconia), non-oxides (carbides, borides, nitrides, and silicides), and mixtures of oxides and non-oxides make up most of the ceramic particles. To increase their durability and defect resistance, these materials are typically changed by adding multiple phases (nanoparticles) and primary and secondary phase materials (fibers and whiskers). When nanoparticles disperse throughout the large ceramic particles, the stress is transferred to these nanonetworks due to their large surface area and aspect ratio (Zhou et al., 2019).

2.1.4. Hybrid

Due to the potential to combine the benefits of both components the stability and optoelectronic features of the inorganic part, and the flexibility and ability to process of the organic part research on solar cells utilizing hybrid nanocomposite layers has increased recently. Hybrid nanocomposite materials can be made of semiconductor nanostructures based on silicon, chalcogenides, and metal oxides, conducting polymers and metal phthalocyanines as p-type materials, and fullerene derivatives and non-fullerene compounds as n-type materials (Socol & Preda, 2021).

2.1.5. Carbon-Based

It is frequently used to combine more than two different solid phase types to make carbon nanocomposite matrixes. The synthesized nanocomposites have remarkable mechanical strength, toughness, and thermal/electrochemical conductivity, among other unique features (Dou et al., 2022a). By linking active components to various carbon-based materials like graphene oxide (GO), carbon nanotubes (CNTs), and mesoporous silica nanocomposite (MSN), naturally occurring substances such as alginate (Alg) can be blended and modified (Rivas-Sanchez et al., 2022).

2.2. Types of Nanocomposite Systems for Photovoltaic Cells

The main problem with solar energy conversion systems is their poor thermal and optical performance. Therefore, it is important to enhance the thermal and optical efficiency of the energy conversion mechanisms (Abd-Elhady et al., 2025). Many nanocomposite materials, such as organic-inorganic hybrids, quantum dot-based, perovskite-based, carbon-based (e.g., graphene, carbon nanotubes), and those incorporating metal nanoparticles, are leveraged precisely for this purpose, offering innovative solutions to optimize the effectiveness of solar energy harvesting technologies, as explained in the following section.

2.2.1. Organic-inorganic hybrid nanocomposites

A combination of organic and inorganic materials with microns scale dimensions is the general definition of organic-inorganic hybrid nanocomposites. For instance, surface modification with organic polymers can make water nondispersible inorganic nanoparticles such as gold nanoparticles (AuNPs), iron oxide (Fe3O4) nanoparticles, semiconductor quantum dots (QDs), carbon dots, etc. dispersible in water (Park et al., 2020). These nanocomposites combine the excellent electrical and optical capabilities of inorganic materials with the flexibility and processability of organic materials. This can enhance the efficiency of charge separation and transport, boost light absorption, and make it possible to create more flexible solar cells. The use of organic and inorganic nanocomposites in light-emitting diodes, photodiodes, and photovoltaic cells is extremely promising (Ujjainkar & Waghuley, 2024). The possibility of inorganic/organic hybrid solar cells to combine the benefits of both components has generated a lot of interest. Inorganic semiconductors, on the other hand, have superior electrical properties, such as a high dielectric constant, charge mobility, and thermal stability, and their nanoparticles exhibit enhanced electronic, photo-conducting, and luminous properties. For instance, a variety of chemically structured organic conducting polymers are appealing due to their ease of production, potential for recycling, affordability, expansion, and suitability as sustainable materials (Hiramoto, 2021; Xie et al., 2020). Hybrid nanocomposites of conducting polymers and inorganic semiconductors show promise for photovoltaic cells by combining absorption bands to enhance solar light harvesting. These materials facilitate photo-induced charge separation mainly at their interfaces, inhibiting electron-hole recombination (Niederhausen et al., 2021).

Organic/inorganic hybrid materials are categorized into two groups based on their binding forces: Class 1 materials have weak interactions like hydrogen bonds or van der Waals forces, while Class 2 materials are strongly bound by ionic-covalent or covalent bonds. Recent advancements focus on creating stable Class 2 hybrids, offering benefits like reduced phase separation and easier interface definition for manufacturing new materials from functionalized alkoxides (Park et al., 2020). Some representative hybrid systems that have been created are as follows: Systems based on quantum dots and nanocrystals, nanorods and nanotetrapods, hybrid systems based on nanoporous inorganic semiconductors, ordered nanorod arrays (NRA) and ordered nanotube arrays (NTA) (K. Chen et al., 2022; Ling et al., 2024; Nagar & Shukla, 2024, 2024; Sun et al., 2025).

2.2.2. Quantum dot-based nanocomposites

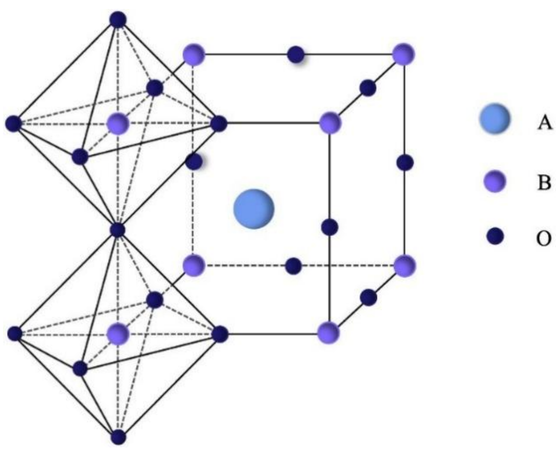
The newest member of the carbon nanomaterial family, carbon dots, are remarkable zero-dimensional carbon nanomaterials with amazing capabilities. These characteristics, which include affordable prices, larger surface area, excellent electron donating/accepting characteristics, low toxicity, luminescence, and photoluminescence (PL), photostability, high quantum yield, and electrocatalysis, make them desirable materials for energy applications such as fuel cells, light-emitting diodes (LEDs), rechargeable batteries, photovoltaics, and metal-air batteries (Elemike et al., 2022). Depending on their size, these nanoparticles have soluble optical and electrical applications. They have a high energy conversion efficiency and can absorb light over a wide spectrum. In multilayer photovoltaic applications, quantum dots are frequently utilized to extract energy from a wider range of light. Because of its outstanding fluorescence features, ecofriendliness, and numerous uses in sensing, imaging, photovoltaic devices, and energy in general, carbon dots are currently in vogue (Agarwal et al., 2023).

Additionally, tunnelling channels that facilitate electron mobility and suppress electron-hole recombination are provided by the nature of carbon dots (Das et al., 2021). This feature will improve photovoltaics' ability to produce extra charge carriers and, as a result, improve their dynamics, which will increase energy efficiency. The ability of carbon dots to form composites with other materials metals, semiconductors, non-metals, etc. by coupling their organic functional groups with other materials is another intriguing characteristic of these particles. This feature increases their range of light absorption and allows them to efficiently photo sensitize (Castillo-Cabrera et al., 2025) and also, CDs are used in the active absorption layers, hole transporting layers, electron-transporting layers, and interlayer spacing of solar cells, which modifies the energy levels of other supporting materials (Elemike et al., 2022). Carbon dots have many uses in bioimaging, optoelectronics, biolabelling, light harvesting and storage, photo blinking materials in multichromophoric systems, catalysts, water treatment, polymer synthesis, antimicrobes, superconducting devices, photovoltaic cells, and energy storage devices, among other areas, due to their special and attractive properties, particularly as fluorescent materials. The characteristics of carbon dots or nanomaterials are significantly affected by doping. According to reports, doping carbon dots with heteroatoms (S, N, P, etc.) enhances their optical characteristics and increases their capacity to capture solar radiation across a broad spectrum. To put it another way, they work extremely effectively in solar cells (H. Li et al., 2020). Quantum dots, which are tiny semiconductor nanostructures, can include the flow of electrons in the conduction band, holes in the valence band, or excitations of bound pairs of electrons and holes in all three spatial directions. With diameters between 2 and 10 nanometers, quantum dots offer unique optical, electrical, magnetic, and catalytic capabilities (Sanmartín-Matalobos et al., 2022). Quantum dots have a distinct quantized energy spectrum. Researchers have discovered uses for them in a variety of fields, including LEDs, transistors, and solar cells (Mimona et al., 2025).

2.2.3. Perovskite-based nanocomposites

Perovskite is the name given to compounds with an ABX3 formula type with cations of different sizes "A" and "B" connected to anion X. Perovskites of inorganic oxide, perovskites of alkaline metal halide, and perovskites of organic metal with oxide or halide anions are the three categories into which these perovskites are separated. Moreover, they can be produced from one- to three-dimensional nanostructures and employed in several environmentally friendly applications. Perovskites with the general formula ABO3 have been used n several gas sensing experiments because of their strong thermal stability and 3.4 eV band gap (T. W. Chen et al., 2020). Figure 2 shows the ABO3 type of perovskites structure.

Figure 2. ABO3 type of perovskite structure (reprinted with permission from ref (Wei et al., 2021). Copyright © 2021, Elsevier)



Perovskites' superior photoelectric efficiency and photoluminescence have led to extensive research into them across a wide range of disciplines and applications (Getachew et al., 2023). Because of their low crystal structure's resistance to moisture, perovskites' luminescence is known to be extremely sensitive to hydron molecules, suggesting a possible use for humidity monitoring (Peng et al., 2022). Recent advances in solar research have made perovskites one of the brightest stars. Their strong light absorption and efficient load bearing capabilities draw attention. Perovskite-based nanocomposites have the potential to boost these materials' stability and enhance their ability to capture light energy across a wide range of wavelengths. The morphology of the films was improved in terms of device performance, crystallization kinetics, and crystal growth by adding nanoparticles to perovskite-based solar cell (T. Wu et al., 2021). Due to their many beneficial qualities, perovskites are a good choice for photon-absorbing materials in solar devices. Crucially, the perovskite layer can be made with low-cost coating and printing techniques, suggesting that developments gained for polymer solar cells will also benefit this novel material system. Perovskites may be made in a trustworthy manner. Over a wide wavelength range, perovskite absorbers have a good absorption coefficient. TiO2 thin films have received a lot of interest due to their wide range of applications, which include electrochromic, photovoltaic, and microelectronic devices (Ali, 2023).

2.2.4. Carbon-based nanocomposites

Carbon-based materials are a preferred material for many applications due to its versatility, which includes the capacity to chemically react with a range of various elements via a strong covalent bond. It demonstrated that materials based on carbon have large densities, high strengths, and high hardness. As a result, there have been several fruitful research resulting from the variety of architectures in various fields of advancements and inventions. High conductivity, mechanical resilience, and chemical stability are provided by these attributes. By serving as electron carrier layers, photovoltaics can enhance charge transport distortions and increase light absorption (Celiktas & Uyan, 2019; Jayan K, 2024; Uyan & Celiktas, 2023). CNTs completes with barriers made of hexagon-shaped graphite and usually long, thin capped ends. SWCNTs are created by a graphene sheet rolling alone, whereas multi-walled carbon nanotubes (MWCNTs) are created by stacking and organizing many graphitic shells (two for simplicity). A single-walled carbon nanotube has a hollow structure formed by covalently bound carbon atoms (Badamshina et al., 2013). CNTs are unique fullerene structures composed of concentric graphite layers. Multi-walled CNTs are held apart by Van der Waals forces, while single walled CNTs consist of a single layer. Their tubular shape resembles buckyballs (C60). Multi-walled CNTs typically have an outer diameter of 2.5–50 nm and an inner diameter of 1.5–15 nm, while single-walled CNTs range from 0.6–5 nm. CNTs can vary in aspect ratios and lengths based on processing methods, impacting their electrical, thermal, and structural properties. Their nanoscale dimensions (less than 100 nm) demonstrate genuine nanotechnology (Arora et al., 2022; W. S. Khan et al., 2022). Graphene is a special two-dimensional nanosheet of sp-2 hybridized carbon atoms that is one atom thick. Because of its exceptional electrical conductivity, flexibility, strength, and heat stability, graphene has been employed as a successful nanofiller in shape memory polymeric nanocomposites (B. Ahmed et al., 2023). In addition to having an extraordinary specific surface area (2630 m2 g−1) and a high Young's modulus (1.1 TPa), graphene is a zero-bandgap semi-metal with ambipolar electrical characteristics and a high thermal conductivity (3x103Wm−1K−1 at ambient temperature). Synergistic effects between G-based materials and polymers result in novel nanocomposites with improved structural and functional properties (Olorunfemi et al., 2022).

The scientific community today is captivated by graphene, a carbon allotrope with unusual mechanical, thermal, and electrical properties that may be organized in a 2D layered form. With the addition of doping and the creation of porous structured graphene, its large surface area can be further adjusted. Furthermore, the hydrophobic characteristics of graphene, a tightly conjugated network (π-conjugation), make it a perfect substrate for the simple immobilization of both organic and inorganic molecules. High conductivity is another property of graphene, which mostly facilitates electron transport on its edge planes. These features include the introduction of doping and the production of porous structured graphene. Furthermore, the hydrophobic qualities of graphene, a tightly conjugated network (π-conjugation), provide an excellent medium for the simple immobilization of both organic and inorganic compounds (T. W. Chen et al., 2020). Because nanocarbon materials have adjustable electrical and optical properties, they are increasingly used in photovoltaic solar systems. These exceptional qualities address wide bandgap energy, charge carrier mobility, sheet resistance, recombination center reduction, corrosion rate and degradation reduction, and are sufficient to meet PVs' criteria. As a result, PV cell modules have a longer lifespan (Olorunfemi et al., 2022).

2.2.5. Metal nanoparticle-incorporated nanocomposites

Nanoparticles provide useful opportunities to investigate changes in material properties as a function of particle size. In the metal category, Au, Ag, and Cu nanoparticles exhibit unique electronic, optical, and catalytic properties that vary according to their size. The properties of these nanoparticles differ significantly from those of bulk metals or molecular compounds, and depend strongly on particle size, particle shape, inter-particle distance, and the nature of the organic shell, if any (Park et al., 2020). Because of the potential of metal nanocomposite materials to improve optical and electrical properties has drawn a lot of interest in recent years. Exciting electronic, optical, catalytic, or photocatalytic capabilities that are partially inherited from parent atoms are present in the compositesHowever, the impacts of various metal nanoparticles on PV output are distinct (Dong et al., 2018). Preferred for its reactive NH groups and wide range of uses in sensors and electronics, polyaniline provides excellent electrical conductivity, environmental stability, affordability, and adaptability. Inorganic fillers can be added to change its conductivity. Zinc oxide is an n-type semiconductor that works well in solar cells and has a broad band gap and good photocatalytic activity. Conducting polymers and inorganic oxide nanoparticles are combined in nano composites to improve the characteristics of both components and increase their potential applications (Emi Princess Prasanna et al., 2022). PV cells employ nanocomposites with various structural configurations. A detailed explanation of the role of nanocomposites in PVs is provided in the following section.

3. Role of Nanocomposites in Enhancing Photovoltaic Performance

Nanocomposites are essential for the optimization of photovoltaic performance by providing road potential for enhancing the productivity and usefulness associated with solar cells. By integrating nanostructures into photovoltaic devices, such as incorporating nanoscale materials into the active layers or interfaces, researchers aim to enhance light absorption, charge transport, and electron-hole separation, ultimately leading to more efficient conversion of solar energy into electricity. This interdisciplinary approach at the intersection of nanotechnology and photovoltaics holds significant potential for advancing renewable energy technologies and addressing global energy challenges. Using a highly reflective nanocomposite coating on solar concentrators is crucial for reflecting solar radiation within the solar spectral area. To absorb the most radiation reflected from the mirror, nanocomposites are also applied selectively to the absorber surface. In the end, various nanocomposites can be applied as thin film coatings to the absorber and reflector to improve the substrate material's optical characteristics (Devasahayam & Hussain, 2020). Polymer composites and semiconducting nanoparticles have earned critical intrigued due to their interesting properties. Polymers provide stability and flexibility, while allowing control over nanoparticle growth. Among these, group II-VI chalcogenide nanoparticles like cadmium sulfide (CdS) are extensively studied for their optical and electrical properties. CdS, with a wide band gap semiconductor and high absorption coefficient, is notable (Z. R. Khan et al., 2010). Polymers like polyvinyl alcohol (PVA) are preferred for thin film fabrication due to their mechanical strength, large band gap energy, and easy controllability over nanoparticle growth (Talib et al., 2024).

Flexible solar cells (FSCs) are gaining attention from researchers aiming to create efficient, portable power sources (R. Wang et al., 2020). Typically, these cells use a flexible plastic substrate coated with indium tin oxide (ITO). However, the fragility of ITO can lead to degradation under harsh bending conditions, reducing power conversion efficiency (PCEThe requirement for completely low-temperature substrate preparation is additional difficulty in perovskite solar cell (PSC) applications (Kim & Kim, 2021). To address these issues, high-flexibility electrode materials with excellent electrical conductivity and optical transparency are required. Materials like graphene, chalcogenide, and nanocomposites of certain 2D materials offer these desired features and are lighter and easier to obtain (Agyei-Tuffour et al., 2022). Efforts continue to enhance graphene's properties by incorporating optimal amounts of metal oxide photocatalysts for high-efficiency renewable solar cell systems. Metal oxide-based nanocomposites have become prominent in photocatalysis due to their stability, nontoxicity, and excellent photocatalytic properties. However, achieving superior productivity with graphene-based nanocomposites as photoanode/counter electrode necessitates an architecture that reduces electron loss and maximizes photon retention at nanostructure associations (Low et al., 2021). Furthermore, the integration of nanomaterials in photovoltaic solar systems not only extends the lifespan of PV cell modules but also enhances their overall performance.

3.1. Advantages of using nanocomposite materials in PV cell technology

Utilizing nanocomposite materials in photovoltaic (PV) cell technology offers a myriad of advantages, each contributing to the optimization and efficiency of solar energy conversion processes. In the following subsections, the detailed exploration of how these materials facilitate light absorption enhancement through plasmonic nanoparticles, improve charge carrier separation and transport, reduce charge recombination losses, and enhance the stability and durability of PV cells.

3.1.1. Light absorption enhancement through plasmonic nanoparticles

In polymer solar cell research, key focuses include improving efficiency, broadening absorption bandgaps, and addressing degradation issues. Material selection for each layer in polymer photovoltaics is crucial for overall device effectiveness (Z.-G. Zhang & Li, 2021). Despite advantages, conducting polymers face challenges like low mobility and narrow absorption range, prompting exploration. Blending conducting polymers with nanocarbon materials offers a promising solution, leveraging nanomaterials' properties for improved device performance (K.V. et al., 2024). Positioning nanoparticles on the front surface of solar cells leads to dangerous obstructions, resulting in reduced absorption at wavelengths shorter than the plasmon reverberation. Conversely, placing nanoparticles on the rear of solar cells can help mitigating these adverse effects (Morawiec et al., 2019).

Photovoltaic (PV) cells capture high frequency radiation, such as ultraviolet (UV) and visible light, to generate power. However, low-frequency radiation, like infrared, typically converts into heat, resulting in inefficiencies. PV solar cells primarily consist of silicon (Si), known for its high surface reflection, causing approximately 30% of sunlight to bounce off, thus reducing conversion efficiency. To counteract silicon's reflective nature, extensive research focuses on coatings for PV panels. Recent advancements propose micro or nano-composite coatings of antireflection compounds, enhancing solar energy conversion. Commonly used antireflection coatings (ARCs) for Si based solar cells include titanium dioxide (TiO_2), zinc sulfide (ZnS), zinc oxide (ZnO) (Maqsood et al., 2023), aluminum iso-propoxide ($C_9H_{21}O_3Al$), aluminum oxide (Al_2O_3) (Zahid et al., 2021), silicon dioxide (SiO_2), silicon carbide/silicon dioxide (SiC-SiO_2), magnesium fluoride (MgF_2), silicon nitride (SiN), and silicon oxynitride (SiON) (Abbood & Abed, 2023). Plasmonic metamaterials push optical field confinement boundaries, enhancing light trapping in thin-film solar cells. Despite bandwidth limitations, they offer promise. Strategies like elliptical nanowires and metallic nanoparticles broaden absorption spectra, improving photon management and sunlight harvesting (Tharwat et al., 2021).

3.1.2. Charge carrier separation and transport improvement

Photovoltaic systems promise clean energy solutions with materials boasting good conductivity, ion intercalation, stability, and tunable band gaps. Evolving from wafer based systems, nanostructured devices utilize distributed heterojunctions for efficient charge separation. Typically employing two materials to generate photocurrent, photovoltaic cells benefit from MXenes' work functions ranging from 2.14 to 45.65 electronvolts. Surface functional groups, like -O and -OH, significantly influence material work functions. Adjusting barrier heights for semiconductors or metal contacts ensures efficient photocurrent generation (Alhamada et al., 2022). Ike et al., 2023 were incorporated Ag/Co bimetallic nanoparticles into PEDOT/PSS hole transport layer (HTL) at concentrations of 0.05%, 0.1%, and 0.15% by weight, enhancing thin-film organic solar cell performance. Devices with Ag/Co doped HTL showed significant improvement over pristine PEDOT/PSS based cells. The optimal Ag/Co blending of 0.1% by weight yielded the highest PCE of 4.21% under ambient laboratory conditions (Ike et al., 2023). Hamed et al., 2023 was synthesized Ag/$CuPO_4$ nanocomposite via wet chemistry for potential use in enhancing thin-film organic solar cells (TFOSCs) by suppressing charge recombination and increasing photon absorption. Incorporating the nanocomposite into a conventional TFOSC architecture, comprising a poly(3-hexylthiophene) (P3HT) and [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) blend, led to notable improvements in device performance. Experimental evidence suggested that the doped active layer outperformed the undoped counterpart, resulting in a nearly 95% increase in the best PCE compared to the reference cell (Hamed et al., 2023).

Zhang et al., 2021, developed a scalable method for fabricating electron transport layers (ETLs) for commercializing perovskite solar cells (PSCs). The method uses open-air and low-temperature ultrasonic spray coating to deposit tin oxide nanocomposite films, achieving high power conversion efficiencies and excellent shelf-life stability. These devices exhibit minimal hysteresis and excellent shelf life stability, retaining about 90% of their initial performance after 2500 hours of storage (J. Zhang et al., 2021).

Rheima et al., 2020 were synthesized a nanocomposite of titanium dioxide (TiO_2) and zinc oxide (ZnO) using a modified sol-gel technique. The nanocomposites exhibited particle sizes ranging from 11 to 27.37 nm, with TEM showing spherical TiO_2 particles within the ZnO matrix. These nanocomposites displayed superior optical absorption properties and were utilized to fabricate a photosensitizer solar cell with an energy conversion efficiency of approximately 4.6% (Mahdi Rheima et al., 2020). Kesinro et al., 2021 were investigated the impact of adding cadmium-doped barium nitrate nanoparticles and a solvent additive (1-chloronapthalene (CN)) to the photoactive medium based on poly(3-hexylthiophene-2,5-diyl (P3HT): [6,6]-phenyl-C61-butyric acid methyl ester (PCBM)). Devices with varying nanoparticle concentrations and 30v% of 1-chloronapthalene were compared to pristine devices. The solvent addition increased efficiency to 3.55% at 0.3 wt.%, up from 3.25% for the pristine device. This was due to improved charge transport, reaching 5.32×10^{-2} $cm^2V^{-1}s^{-1}$ (Kesinro et al., 2021).

Hu et al., 2019 were developed new composite hole-transport materials (HTMs) for MAPbI3 based perovskite solar cells (PSCs), consisting of non-peripheral octamethyl-substituted copper (II) phthalocyanine (N-CuMe2Pc) nanowires and poly(3-hexylthiophene) (P3HT). Adjusting the component ratio can achieve a PCE of up to 16.61%, surpassing standard devices. Moreover, long-term stability greatly improves, with devices retaining 90% of their initial efficiencies after 800 hours of storage at 75% relative humidity. This highlights the promise of N-CuMe2Pc nanowire/P3HT nanocomposites as effective HTMs for superior PSC performance (Hu et al., 2019).

Dou et al., 2022 introduced a graphene polymer nanocomposite, like PM6 or PM7 Lewis base conductive polymer, during the antisolvent step of Cs/FA/MA perovskite fabrication (Dou et al., 2022a). Through their profoundly conductive nature, the nanocomposites enabled charge transportation and reduced interfacial charges while also facilitating charge recombination through traps. PSCs with graphene-PM6 composite additives achieved a remarkable 21.21% PCE, compared to 18.21% for the control device, with Voc of 1.17 V, Jsc of 24.03 mA cm^{-2}, and FF of 76%. Moreover, due to their hydrophobic nature, graphene PM6 and graphene PM7 based devices demonstrated outstanding stability, retaining 90% and 85% of their initial PCE after 480 hours of aging under ~35% RH at room temperature, respectively (Dou et al., 2022a).

Safari et al., 2019 investigated inverted planar perovskite solar cells (PSCs) using different polymers. They found that employing Poly-TPD enhances the interface with the perovskite-polymer composite layer, improving electron and hole transport and reducing recombination. This driven to an increment in device execution to 15% PCE. Additionally, the photovoltaic characteristics, notably the fill factor (FF), showed slight dependence on the molecular weight of Poly-TPD, allowing for the fabrication of a champion device with high molecular weight Poly-TPD achieving a PCE of 16.3% (Safari et al., 2019).

3.1.3. <u>Reduction of charge recombination losses</u>

In all solar cells, nonradiative recombination losses, caused by factors like defect assisted recombination and electron-phonon coupling, inevitably deviate key performance parameters such as open circuit voltage (Voc), short circuit current density (Jsc), fill factor, and PCE from their optimal radiative limits (Dou et al., 2022). These challenges have prompted exploration into innovative materials and structures to mitigate such losses and enhance overall device efficiency. Nanofibers have recently gained attention in solar cells for their enhanced charge collection efficiency, yet their low surface area limits significant improvement in DSSC performance compared to nanoparticles. Advanced third generation solar cells utilize structured nanofibers, like hollow and core shell varieties. TiO_2 nanoparticles exhibit superior PCE, but suffer from high recombination due to grain boundaries and defects (Kumari et al., 2019; Nien et al., 2019). Conjugated polymers offer promise with their combined electronic and optical properties, enabling diverse applications in flexible electronics. Polymer solar cells, particularly with the bulk heterojunction structure, efficiently separate excitons, making them promising for flexible and lightweight alternatives to silicon based cells (Shalan et al., 2019).

3.1.4. ***Enhanced stability and durability of PV cells***

Enhanced stability and durability of PV cells are paramount for ensuring the long-term reliability and performance of solar energy systems, especially in demanding environmental conditions and prolonged usage scenarios. By addressing degradation mechanisms and improving the resilience of photovoltaic materials and components, researchers strive to prolong the lifespan and efficiency of solar cells, thereby facilitating their widespread adoption and contributing to the sustainability of renewable energy infrastructure. The predominant problem associated with the photovoltaic solar cell is its temperature operation. The superior surrounding temperature since of the solar cannot perform appropriately and the cooling device need to be utilized. Applying the nanoparticles (TiO_2) with a polymer coating to the photovoltaic cell surface facilitates improving strength efficiently. The utilization of the aggregate of TiO_2Np with a polymer withinside the coating of solar cells facilitates defending those cells from dust aggregation and contributes to lowering the impact of excessive temperature (Hachim et al., 2021).

The use of multi junction (MJ) solar cells, as seen in the next generation solar device, can lead to greater efficiency than Shockley-

Queisser restrictions for single junction cells due to the fact that a significant amount of sunlight is taken up while lingering on warm weather (W. S. Khan et al., 2022; Yamaguchi et al., 2021). The multi junction (MJ) solar cell, composed of stacked sub-cells with varying bandgaps, reduces lattice thermal losses, enhancing PCE. Primarily used in space applications, MJ cells offer high reliability, a favorable power to mass ratio, and remarkable radiation hardness (Yamaguchi et al., 2006; Zeitouny et al., 2017). Typically, upper subcells utilize wider bandgap III–V compound semiconductors, while lower sub-cells employ narrower-bandgap III–V or group IV semiconductors like Ge and Si (Shigekawa et al., 2020; Yamaguchi et al., 2021). MJ cells with combinations such as such as GaInP/(In)GaAs/Ge (Thomas et al., 2015) and GaInP/GaAs/InGaAs (Liu et al., 2023), InGaP/(Al)GaAs/Si and In(Al)GaP/GaAs/InGaAsP/InGaAs have exhibited excellent performance.

Self-cleaning coatings for PV panels and architectural glass, utilizing hydrophobic and hydrophilic treatments, have gained attention. These coatings aim to remove dirt and contaminants without external cleaning, harnessing water or airflow for the task (Syafiq et al., 2022). Yang et al., 2024 developed a TiO_2–SiO_2-PAA nanocomposite super hydrophilic coating for PV panels. Adding PAA improved superhydrophilicity, toughness, and antireflection. Long-term outdoor tests (1 to 4 years) measured changes in transmission and self-cleaning efficacy. Results varied: RSCE for PET started at 2%, rising to 15% after 150 days and stabilizing at one year. For glass, RSCE was 4% for 3 years, dropping to 2% in the fourth year, correlating with a 2.8% increase in PV power generation (Yang et al., 2024).

4. Recent Advances and Applications

New nanostructured materials are being designed and developed more rapidly because of advances in solar cell efficiency due to the manufacturing techniques used with advanced nanotechnology. The optical and electronic characteristics of functional layers are influenced by nanomaterials and nanostructures, which modulate their morphology, microstructure, and surface states, leading to significant changes in output voltage and conversion efficiency. For this reason, research and development studies on the applications of nanostructures in PV cells have gained increasing interest. The recent advances and applications of nanostructures in PV cells are demonstrated in the following sub sections.

4.1. Emerging nanocomposite materials for PV cells

Currently, there are several new applications for EPV systems, including organic solar cells, dye sensitized solar cell, perovskites solar cell and quantum dot solar cell, which open up new possibilities with their light characteristics, flexible design and low cost production (Gressler et al., 2022). The most common solar cells available are silicon based and have high production costs. Therefore, many efforts have been made to develop low cost polymer solar cells based on light, flexible and highly absorbent polymer materials (Gong et al., 2020). Polymer solar cells aim to reduce production costs compared to silicon based ones. They utilize lightweight, flexible polymers like polyaniline, which can easily switch between conductive and non conductive states. Composites with minerals and magnetic substances offer unique properties. Combining polyaniline with TiO_2 enhances electrical conductivity (Sadegh et al., 2023).

Titanium dioxide (TiO_2) nanocomposite material was utilized in this investigation in various concentrations with polymer. The PV efficiency and solar radiation antireflection are both significantly improved by this application. The PV Polycrystalline solar cell was coated in order to decrease the amount of low frequency infrared radiation (IR) absorbed and to enhance the electron's excitation process to sunlight (Shahat & Ghitas, 2022; Tale et al., 2021). High performance is demonstrated by the polymer composite and one and two layers of titanium dioxide in the experimental test. Whereas the efficiency increases by 1.11% and 2.71%, respectively, with one layer and two layers for the initial concentration (CO1). For one and two coating layers, the improvement in efficiency is approximately 0.473% and 1.59%, respectively, when the second concentration (CO2) is used (Hachim et al., 2021). Appasamy et al. 2019 into and assessed the possibility of using a novel photocatalyst nanocomposite made of nitrogen doped titanium dioxide and single-wall CNTs (N-doped TiO_2/SWCNT) for self-cleaning coating application on solar PV panel surfaces. Sol-gel synthesis was used to create the N doped TiO_2 photocatalytic powder, which was subsequently impregnated with SWCNT by altering the compositions of TiO_2 and SWCNT (Appasamy et al., 2020). Jarrahi et al. 2023 present intensive research encompassing the synthesis of raw substances to the evaluation of photovoltaic cell performance. The study consists of the manufacturing of the polyaniline/cadmium sulfide hybrid nanocomposite the use of a one pot method, an exam of morphology, the improvement of a hybrid organic/inorganic solar cell, and the evaluation of cell performance (Jarrahi et al., 2023). CNTs together with decreased graphene oxide (RGO) are synthesized the usage of modest techniques and their composites with the polymers PEDOT:PSS and P3HT are organized the usage of an easy solution method. The incorporation of filler carbon nanomaterials has been observed to achieve success in appreciably prolonging the steadiness of the OSCs even as retaining the augmentation in PCE. For the great performing devices, the incorporation of CNTs and RGO has stronger the PCE with the aid of using 12.52% and 13.21% and advanced the device lifetime with the aid of using 37.31% and 43.23%, respectively (Subramanyam et al., 2020). From raw material extraction to production and recycling, solar cell manufacturing involves energy consumption and chemical use. There's also concern about toxic substance release, including heavy metals from damaged modules. Emerging photovoltaic (EPV) systems, like organic solar cells (OSC) and dye-sensitized solar cells (DSSC), utilize Critical Raw Materials (CRM) or New Advanced Materials (AdM). EPV offers flexibility for applications like smart textiles and car roofs, with carbon based substrates reducing CO_2 emissions compared to glass. Flexible polymer or bio derived nanocellulose substrates are viable alternatives for EPV production (Dallaev et al., 2023).

4.2. Future directions and challenges in the field (Integration of nanocomposites into flexible and transparent PV devices)

Solar photovoltaic innovation has noteworthy progresses in both materials and frameworks, driving to advancements in productivity, cost, and energy storage capacity. This progress has made solar photovoltaic innovation a more reasonable choice for renewable energy generation and storage. Nevertheless, discontinuous could be a major restriction of solar energy, and energy capacity systems are the favored arrangement to these challenges (Martín, 2022). Thus, the sort of energy storage system depends on the innovation utilized for electrical generation. Besides, the developing requires for renewable energy sources and the need for long term energy arrangements have fueled investigate into novel materials for solar photovoltaic systems (Dada & Popoola, 2023).

Among different areas of photovoltaic innovations, the bulk heterojunction natural solar cells (OSC) have appeared to be greatly promising candidates due to their low material cost, straightforward manufacture strategies, and adaptability. However, organic photovoltaic cells still have low control transformation productivity (PCE) about other competitive innovations (Okai et al., 2023). Solar cells, as a profitable source of renewable energy, are in any case to some degree expensive when compared to fossil fuels utilized to produce power. Although solar cells have a low productivity, with a greatest of 30 percent, the most widely utilized kind contains a 15–

20 percent efficiency. Lately, including nanomaterials, such as fullerenes, CNTs (Abohamzeh et al., 2022), and quantum dots (S. Wang et al., 2023). to solar cell may increment its productivity (Ge et al., 2021). Essentially, nanotechnology method can be advantageously utilized to construct up high solar cells with high productivity and low cost (Hussein, 2023).

Solar cells position themselves as an appealing alternative to illuminate these days issues of finding a viable, renewable, feasible and green energy source. A couple of materials have been outlined to be effective as the energetic component of said device. Whereas completely adaptable photovoltaic devices have improved, they are still not at the required level (Baran et al., 2020). The 2D material based composites shown different boosted properties, such as moved forward mechanical quality and adaptability, upgraded electrical conductivity, tall optical straightforwardness, high resistance to chemicals and fire, high strength-to-weight proportions, wear resistance, and erosion resistance (Qadir et al., 2021). Joining the 2D boron nitride nanosheets into the polymer can move forward the polymer nanocomposites' optical, mechanical, and electrical qualifications. The gathering of the 2D nanomaterials sheets into a requested structure will altogether affect their mechanical applications. The next generation circuits can be presented by planning the 2D monomers and directing them into a craved collected structure. The qualifications and the viable usage of ultrathin 2D nanomaterials depend upon the effective blend of these materials (Baig, 2023).

Carbon based nanomaterials, especially CNTs, which are among the 2D materials have picked up seriously research consideration within the manufacture of organic solar cells (OSCs) due to their exceptional physicochemical properties, low-cost, environmental invitingness (Jin et al., 2016; Lazzarin et al., 2021). In this respect, the low sheet resistance and high optical transmittance of CNTs empowers their application as elective anodes to the broadly utilized indium tin oxide (ITO), which is harmful, costly and rare. Moreover, the cooperative energy between the large particular surface region and high electrical conductivity of CNTs gives both large donor-acceptor interfacing and conductive interpenetrating systems for exciton separation and charge carrier transport (Muchuweni et al., 2022). The conventional backsheet typically consists of three layers: a PET polyester film core coated with PVDF on both sides using an adhesive. However, PET films have limited chemical stability and thermal conductivity. In contrast, CNF films offer excellent mechanical and optical properties, meeting backsheet requirements (Y. Zhang et al., 2020). Photoanode, which is one of the major components underpins sensitizer and transport photo-excited electrons from exciter to outside circuit, which needs large surface range and ensures electron collection proficiency. In order to improve these properties nanoparticles of diverse shapes and structure, diverse materials have been investigated. Although TiO_2 demonstrated to be the productive material for DSSCs, the quick recombination rate, long term steadiness, weakly bound dye particles and constrained photo reaction of TiO_2 has prevented its commercialization (Boro et al., 2018; Gnida et al., 2021).

In conclusion, while nanocomposite materials offer promising advantages in PV cell technology, addressing challenges and exploring future directions will be crucial for maximizing their potential in advancing solar energy applications.

4.3. The Future of Nanocomposite Technologies in the Solar Energy Industry (Commercialization prospects and market trends)

Nanocarbon structures like GQDs, CNTs, and graphene hold significant promises for future technologies due to their processability and remarkable properties (Kalluri et al., 2023).

Hybrid photovoltaic materials, combining polymers and nanocarbons, offer enhanced performance in organic solar cells, particularly in charge transport layers. These composites exhibit superior electronic and optical properties, leading to improved device performance. Research on polymer-nanocarbon composites for next-generation technologies shows promising results, with potential for broader applications because of their mechanical strength, flexibility, and low-cost manufacturing. Exploring the synergy between polymers and nanocarbons for optimized charge transport represents a promising research direction for the near future (K.V. et al., 2024). The current landscape of the solar energy market is tightly intertwined with rapid technological advancements, shaping both its growth trajectory and the evolution of renewable energy solutions. The worldwide market for nanocomposite solar cell market is valued at $4.2 billion in 2022, set to grow at a substantial CAGR of 12.4% to reach $13.5 billion by 2032, representing over 5% of the total solar cell market. This growth is propelled by the worldwide shift towards renewable energy sources, driven by increasing environmental awareness and efforts to reduce carbon footprints. Term (2025-2028), North America and East Asia will likely see heightened demand, while long term demand (2028-2032) will be driven by the adoption of durable and cost-effective solar panels (*FactMR*, 2022). In conclusion, the dynamic interplay between technological innovation and market demand continues to propel the growth of the solar energy sector, with nanocomposite solar cells emerging as a significant contributor. As industry moves towards sustainability, the evolution of nanocomposite technologies stands at the forefront, offering promising solutions for advancing renewable energy goals and mitigating environmental impacts.

4.4. Sustainability Evaluation of Nanocomposite Technologies

It is very important to assess the sustainability of current and future nanotechnology products or where they play a key role. An objective viewpoint is necessary to evaluate the viability of nanotechnology products, providing a suitable framework for evaluating their products and processes, particularly those with long-term economic, social, and environmental consequences (Carroccio et al., 2022; Kamali et al., 2019). Polymer nanocarbon composites have superior adjustability of optical and electronic properties by straight forward compositional building and improve the strength of polymer hybrids. They are accessible to large scale generation so increment the natural compatibility. Moreover, nanocomposites are cost effective compared to other solar cell materials. Hovewer, the union of hybrid materials is more modern compared to their non-hybrid partners and they have challenges in mixing polymers with nanocarbon materials to induce ideal optical and electronic properties (Ehsani et al., 2021). The utilize of nanocomposites in eco friendly applications holds promise for advancing towards a carbon-neutral society. Leveraging their special qualifications, nanocomposites offer a sustainable alternative to conventional materials, aiding in reducing carbon emissions. Surveying the environmental effect of nanocomposites can direct their utilize and recognize areas for advancement. Research into nanocomposite manufacturing is crucial, as the process significantly influences their performance and properties. Optimizing the manufacturing process can enhance the quality and consistency of nanocomposites, further supporting their widespread adoption (Saharudin et al., 2023).

4.5. Environmental Impacts and Green Nanotechnology Strategies

Nanotechnology reshapes the future of solar energy collection by innovating material and device structures for photovoltaic cells, enhancing efficiency, cost effectiveness, and stability. Breakthroughs like multi junction and perovskite solar cells show impressive efficiencies, cutting material usage and fabrication costs. Future focus should prioritize cost effective and eco-friendly materials, like bio based options, to advance photovoltaic cell technology (Rajbongshi & Verma, 2019). Nanotechnology offers notable health and environmental benefits, contributing to cleaner and greener advancements. Its applications extend to managing, mitigating, and cleaning up air, water, and land pollution, as well as improving the performance of traditional environmental cleanup technologies. Green nanotechnology, focused on sustainability, explores various applications to address these challenges (S. H. Khan, 2020). Green nanotechnology utilizes natural pathways like microbial or plant-based extracts to synthesize nanoparticles, creating environmentally friendly materials devoid of harmful substances. By employing bio-reduction of metal ions with plant components, nanoparticles can be generated in a greener way. This approach has been successfully applied to produce various nanoparticles, including silver, gold, palladium, iron, and zinc oxide (Alqarni et al., 2022; Arora et al., 2022). Nevertheless, nanotechnology presents a sustainable solution for mitigating climate change's environmental impacts. While Life Cycle Assessment (LCA) is effective for evaluating materials and products, assessing nanomaterials in LCAs faces significant data gaps and uncertainties regarding properties, toxicity, and environmental effects. Therefore, improvements are essential for a more thorough analysis of nanomaterials' life cycles (Chausali et al., 2023).

5. Conclusion

In conclusion, the integration of nanocomposite materials into photovoltaic (PV) technology represents a necessary progress with the potential to revolutionize the renewable energy landscape. Throughout this chapter, we have explored the multifaceted role of nanocomposites in enhancing the efficiency, reliability, and sustainability of PV cells. From their ability to improve light absorption and charge carrier dynamics to mitigating recombination losses, nanocomposites offer promising solutions to current challenges facing PV technology. Despite the promise, several hurdles remain, including cost, efficiency, and adaptability issues. However, ongoing research and development efforts focused on areas such as life cycle assessment, composite manufacturing, coating technologies, and materials engineering are steadily addressing these obstacles. Collaboration across industries and disciplines is essential for expediting the development and selection of eco-friendly nanocomposites. Advancements in nanotechnology have led to greater solutions for global sustainability challenges. Developments in nanotechnology lead to progress in clean energy technologies and therefore serve the targets of Sustainable Development Goals 7 and 11. This alignment with sustainable development objectives underscores the potential of nanocomposite solar cells to contribute significantly to the transition to carbon neutrality and the broader goals of environmental stewardship. The potential applications of nanocomposites extend beyond PV technology, encompassing lightweight composites for electric vehicle components, bioplastics, and biocomposites, further underscoring their significance in achieving a carbon-neutral society. With proceeded attempt focus on this promising field, economical nanocomposites have the potential to shape a more maintainable future for eras to come, decreasing carbon emanations and progressing toward a cleaner, greener world.

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CHAPTER 2

CARBON BASED NANOMATERIALS: A REVIEW ON BIOBASED QUANTUM DOTS

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1.Introduction

Studies on carbon-based nanomaterials such as carbon nanotubes, graphene and its derivatives, nanodiamonds, and other nanosized carbon allotropes have shown a remarkable increase in recent years (Díez-Pascual, 2021; Rao et al., 2021; Zaytseva & Neumann, 2016).

Carbon-based nanomaterials have gained attraction due to their outstanding properties, including mechanical, chemical, and thermal stability; durability to corrosive chemicals; good thermal and electrical conductivity compared to higher density materials such as metals and alloys; having functional groups on the surface;

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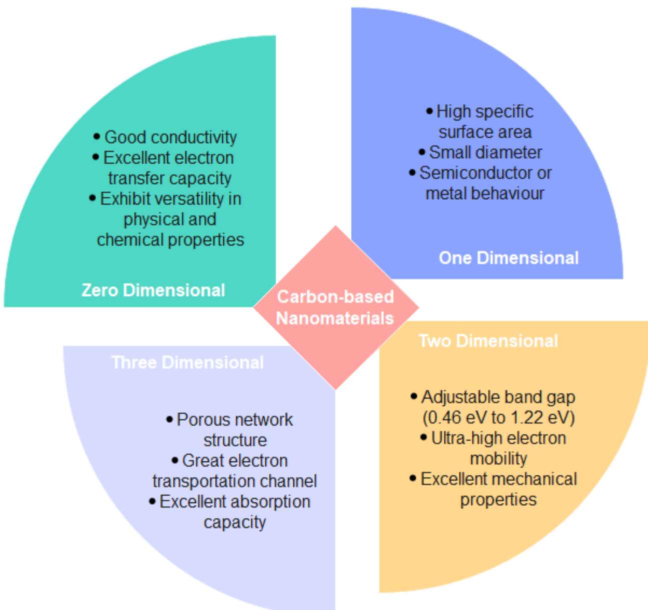
and enabling enhancement through doping materials (Ruiz-Perez et al., 2022).

Carbon-based nanomaterials and their products have a wide range of applications, including wastewater treatment, metal ions, dyes (Soffian et al., 2022), electrode materials in energy storage devices (Celiktas & Alptekin, 2019), electrocatalysts within oxygen reduction reaction, oxygen evolution reaction, hydrogen evolution reaction (Cheng et al., 2022). They can be categorized as zero-dimensional (0D), one-dimensional, two-dimensional, and three-dimensional. Photoelectric properties, which are very important on the quantum efficiency of various carbon-based materials classified according to size, are presented in Figure 1. Extensively utilized carbon materials comprise of carbon nanotubes (CNT), graphene, activated carbon, and carbon-based quantum dots (Ye et al., 2022).

Figure 1 Photoelectric properties of carbon-based materials (Fang et al., 2020; Tong et al., 2024).



Carbon quantum dots have become an increasingly notable material in the carbon family due to their excellent and tunable photoluminescence (PL), high quantum yield (QY), low toxicity, small size, remarkable biocompatibility, and low cost. Carbon quantum dots (CQDs), which are typically less than 10 nm (C et al., 2025; Navidfar et al., 2022; Sefid-Sefidehkhan et al., 2022; Van Tran et al., 2022; J. Zhang et al., 2022) have become the focus of interest among carbon-based nanomaterials due to their superior physical and optical properties (Yan et al., 2023), standing among nanomaterials, for their good biocompatibility, low toxicity, adjustable optical properties, low preparation costs, and low environmental impact. These properties of CQDs reveal their potential for various applications such as drug delivery, bio-imaging, antiviral therapy, and wound healing (Z. Dong et al., 2022; Yan et al., 2023). Carbon quantum dots (CQDs) can also be used in biochemical analysis, detection, and optoelectronic devices due to their high photoluminescent efficiency (Caglayan et al., 2022; L. Zhang et al., 2023). Photoluminescent properties of CQDs enable their usage in especially biological applications (Arya et al., 2020; R. Zhao et al., 2022). Moreover, food packaging has become a new area as a result of the antibacterial and antioxidant activities of CQDs. CQDs have abundant surface functional groups that can provide good electron mobility for utilization in wastewater treatment (Ezati et al., 2022; Manikandan & Lee, 2022) .

Numerous simple and low-cost methods have been developed for synthesizing CQDs, including top-down and bottom-up approaches (Kim et al., 2022; Yan et al., 2023). The top-down method is used to break up bulk materials utilizing physical, electrochemical, hydrothermal, and ultrasonic techniques (Shaari et al., 2021). However, since CQD production by top-down methods require costly precursors and complex processes, researchers have turned to the bottom-up CQD method, which not only uses low-cost raw materials but also suitable for large-scale production (Nallasamy et al., 2025; J. Zhang et al., 2022). Bottom-up methods, including the soft-template method and the hydrothermal method, can be used to produce CQDs from natural sources in greenways (Cebi et al., 2022; Pan et al., 2020). Hydrothermal synthesis has become a popular method among researchers due to its ease of use, speed, and ability to produce less gaseous products while having a porous structure with a high specific surface area (Kazan et al., 2015; Mathew et al., 2022; Quan et al., 2022).

Commonly used raw materials to produce CQDs include expensive materials such as carbon nanotubes, graphene, and coal, and these raw materials are toxic and difficult to purify (J. Zhang et al., 2022), whereas the synthesis of natural carbon sources is reproducible and environmentally friendly. Green synthesis with low-cost sustainable features is also gaining more and more attention (Nair et al., 2020). Green synthesis of CQDs consists of green feedstock and methods that comprise microwave, pyrolysis, ultrasonic, hydrothermal, etc. (Y. Han et al., 2022).

Biomass resources are widely used to produce carbon materials because of their sustainability and abundance (Tohamy et al., 2022; Uyan et al., 2019). They contain cellulose, hemicellulose, and lignin and are known as suitable materials for producing porous carbon materials with high porosity (Alptekin et al., 2023; Muge Alptekin & Soner Celiktas, 2022; Uyan et al., 2020; Xu et al., 2025). For this reason, they are extensively preferred as precursors in carbon quantum dots production (Lin et al., 2022).

This chapter discusses the synthesis methods and application areas of carbon quantum dots with the use of biobased materials, which have attracted considerable attention in recent years among carbon nanomaterials and have provided significant advances in the design of robots, devices and sensitive sensors in biomedical applications. Additionally, the pros and cons of bio-based and commercial CQDs are presented, taking into account their important features in serving different areas of use. Hence, it is aimed to guide researchers working in this field to fully discover the remarkable properties of CQDs, which are preferred in many advanced applications, and to pave the way for the use of biobased CQDs in many other application areas.

2. Production Methods of Bio-based Carbon Quantum Dots

Biomass feedstocks are of significant interest in the production of CQDs due to their high carbon and oxygen content. Their biodegradability and high water solubility render these material attractive precursors for CQDs production (Bijoy & Sangeetha, 2024). Since biomass sources with rich carbon and oxygen content include heteroatoms such as nitrogen (N), sulfur (S), and silica (Si), CQDs produced using biomass sources demonstrate self-doping properties (Jones et al., 2017).

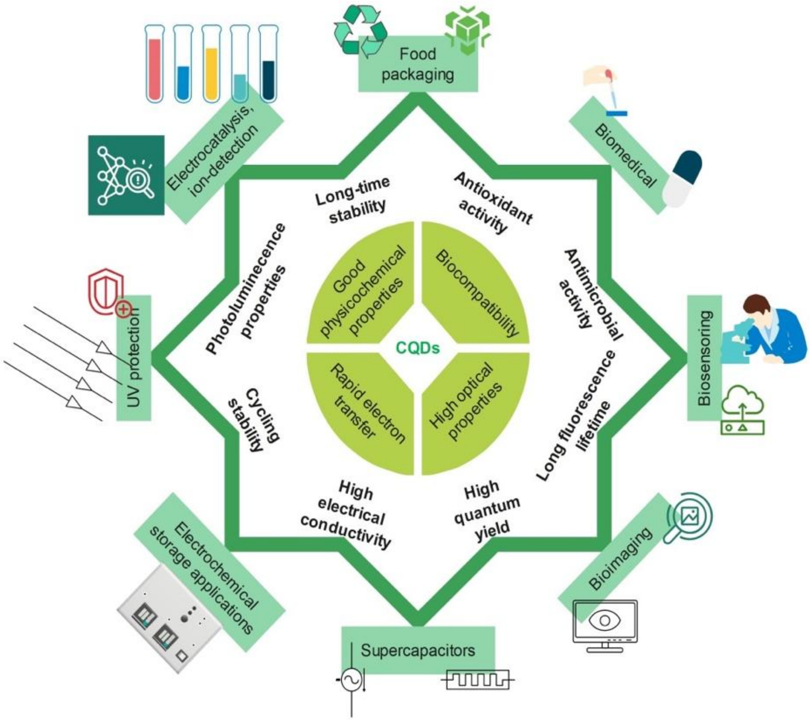
To use in sensing heavy metal applications, CQDs require a fluorescence quantum yield efficiency greater than 10%. Nitrogen (N), sulfur (S), and boron (B) doping increase the fluorescence quantum yield and detect sensitivity (Bahtiar et al., 2022; Q. Liu et al., 2025). Moreover, functional groups such as –OH, $-NH_2$, and –COOH are used for creating fluorescence through a chemical enhancement process (Umar et al., 2023). However, compared to surface passivation or functionalization, heteroatom doping is considered a more effective and time efficient method for enhancing low quantum yield (Karadag et al., 2022).

CQDs are synthesized with traditional methods that are generally known as bottom-up and top-down methods. While top-down methods include laser ablation, arc discharge, and chemical oxidation, bottom-up methods contain hydrothermal treatment, pyrolysis, and microwave irradiation (Q. Liu et al., 2025; Moradi et al., 2021; D. D. Nguyen & Lai, 2022). Carbonaceous macromolecules like graphene, carbon nanotubes, and activated carbon are dispersed into nano-sized CQDs by various methods in the top-down strategies while small carbonaceous precursors are employed to fabricate CQDs by a sequential reaction of polymerization and carbonization in the bottom-up strategies (Azam et al., 2021), favored in carbon quantum synthesis using biomass sources (Lim et al., 2015). Hydrothermal treatment is widely used in biomass-derived CQDs due to their easy processability and affordability compared to other bottom-up methods (Z. Zhu et al., 2020).

CQDs produced by conventional bottom-up methods using biomass sources have good photoluminescence properties and quantum yield. However, new synthesis strategies are being developed to improve the quantum yields and luminescence properties of CQDs, combining bottom-up and top-down methods to provide methods for the production of high-quality CQDs (Y. Liu et al., 2020). Jing et al. (2019) synthesized biomass-derived CQDs from glucose with this new strategy. The CQDs were fabricated in two steps, first producing hydrochar from glucose via hydrothermal treatment and then treating the hydrochar with NaOH. Finally, the CQDS were fabricated with high quality and high product yields (43.8 wt %) (Jing et al., 2019). Wang et al. (2016) utilized a new two-step synthesis method to produce CQDs from rice husk. They treated rice husk produced from the pyrolytic process with H_2SO_4 and HNO_3. The CQDs obtained demonstrated good photoluminescence properties together with a high product yield of 25 wt % (Z. Wang et al., 2016). The results show that the hydrothermal method combined with chemical oxidation is a promising method for large-scale production of CQD using biomass, resulting in improved product yield (Y. Zhao et al., 2020). The surface functional groups of CQDs are crucial owing to their effect on light emission. Thanks to different synthesis methods, these groups can be modified (Cui et al., 2021).

Implementation of carbon quantum dots (CQDs) as shown in Figure 2 include, but not limited to, bio-imaging, sensors, bio-medical, catalysis and solar cells (X. Guo et al., 2017). In the following section, the application fields of CQDs are reviewed in detail.

Figure 2 Superior properties and wide application areas of bio-based carbon quantum dots



3. Application Fields of Bio-based CQDs

Good physicochemical properties, biocompatibility, rapid electron transfer, and high optical properties of CQDs suggest desirability in various applications. Research studies on the

production of biobased CQDs are classified according to their current applications under 4 sections, in the fields of biomedical, environmental, energy and food areas. The emerging applications of biobased CQDs are separately discussed in the 'New Era' section. The reviewed research studies that included wide range of application areas of CQDs from different bio-based feedstocks are shown in Table 1.

Table 1 CQDs derived from different bio-based feedstocks and their applications

Bio-based Feedstock	Method	Application	References
Ginkgo leaves	Hydrothermal	Bio-imaging in HeLa cells and detecting Hg^{2+} in lake water	(Q. Zhang et al., 2019)
Banana peels	Hydrothermal	Bio-imaging in nematodes	(Atchudan et al., 2021)
	Hydrothermal	Supercapacitor electrodes	(T. N. Nguyen et al., 2022)
Rice residue	Hydrothermal	Fe^{3+} detection and bio-imaging	(Qi et al., 2019)
	Hydrothermal	Disinfects bisphenol A (BPA) in water effectively	(Si et al., 2021)
	Ultrasound-assisted one-pot oxidation	Monitoring lake, river, and wastewater treatment	(Bianchini et al., 2023)

Alkali lignin	Hydrothermal	Cellular imaging	(Y. Shi et al., 2019)
	Hydrothermal	Bio-imaging implementations	(Xue et al., 2019)
	Hydrothermal	Bio-imaging and metal detection	(B. Zhang et al., 2019)
Lignin	Hydrothermal	Detecting Fe^{3+} ions	(L. Zhu et al., 2021)
Lemon grass	Hydrothermal	Bio-sensing and optoelectronics applications	(Thota et al., 2018)
	Hydrothermal	Removing methylene blue (MB) dye	(Tyagi et al., 2016)
Platanus	Pulsed laser ablation	Bio-imaging applications	(Ren et al., 2019)
Citric acid	Pyrolysis	Detecting Fe^{3+} ions	(Y. Li et al., 2021)
	Hydrothermal	Water-permeable pervaporation membranes for desalination	(J. Sun et al., 2022)

Microwave-assisted solvothermal synthesis	Quantum dot-sensitized solar cells (QDSCs) as light harvester	(Riaz & Park, 2022)
Hydrothermal	Writing ink	(X. Sun et al., 2017)
Solution process using ionic liquids	Green inhibitors to improve the corrosion resistance of steel	(Yang et al., 2019)
Microwave-assisted method	Reduced the inherent incompatibility between the metal oxide and organic active layers in solar cells	(Magesh et al., 2022)

N-doped Asparagus, white radish, and potato	Solution impregnation	Catalysts in hydrogen production	(S. Chen et al., 2022)
N and S co-doped Sodium citrate and thiourea	Hydrothermal	Gradually increasing/decreasing temperature sensor	(Z. Han et al., 2019)
Wood	Hydrothermal	pH detector feature for wearable technologies	(X. Tao et al., 2022)
Chicken feather	Hydrothermal	detecting Hg^{2+} ions	(Dhandapani et al., 2023)
Lotus stem	Hydrothermal	Ferric ions detection in wastewaters	(Qureashi et al., 2021)
Kraft pulp	Solution process	Detecting Fe^{3+} ions	(Woo et al., 2020)

	using ionic liquids		
	Hydrothermal	Anti-counterfeiting inks	(Park et al., 2020)
Chitosan	Hydrothermal	Detection property for iodine ions	(J. Song et al., 2018)
	Hydrothermal	Solar cell applications	(Gomes et al., 2019)
Orange peel	Hydrothermal	Detection of Fe^{3+} ions in pond water	(C. Wang et al., 2020)
	Microwave-assisted solvothermal synthesis	Photoanodes in solar cells	(Olmos-Moya et al., 2022)
	Hydrothermal	Optically switched photonic devices	(Surendran et al., 2020)
	Solution impregnation	Photocatalytic CO_2 decrement	(J. Zhang et al., 2021)
Waste tea extract	Hydrothermal	Detect CrO_4^{2-}, Fe^{3+} and be used	(K. Chen et al., 2019)

		as fluorescent nano-sensors	
	Hydrothermal oxidation	Supercapacitors	(Inayat et al., 2023)
	Solvent casting	Packaging material for grapes	(Patil et al., 2020)
Pear juice	Hydrothermal	Degradation of methylene blue (MB)	(Das et al., 2019)
Pomelo peel	Hydrothermal Oxidation	Electrode materials for supercapacitors	(Zhuang et al., 2022)
Mustard flower	Hydrothermal	Down-conversion light-emitting diodes and optical displays	(Sharma et al., 2023)
Soybean powder	Hydrothermal	Enhance conversion efficiency of the solar cells	(Meng et al., 2017)

Bamboo	Hydrothermal	Cathode exchanger layers in PV applications	(Juang et al., 2018)
Grape leaves	Hydrothermal	Food packaging	(Khoshkalampour et al., 2023)
Red beet pigment	Hydrothermal	Fluorescent detection probe for tetracycline (TET) residue from animal derived foods	(Cao et al., 2022)
Beet root extract	Hydrothermal	Tissue engineering	(Praseetha et al., 2021a)
Aloe peel	Anaerobic co-digestion	Accelerators in anaerobic co-digestion systems	(L. Liu et al., 2023)
Starch	Microwave-assisted method	Rapid latent fingerprint detection	(X. Wang et al., 2022)

Bell pepper	Hydrothermal	pH-modulated fluorescence switching nano-sensor	(G. Guo et al., 2024)
Chinese herb mulberry	Hydrothermal	Osteoblast gene markers	(Q. Zhang et al., 2024)
Okra	Hydrothermal	Dichlorvos (DDVP) monitoring in foods	(Mei et al., 2024)
Antimicrobial bacterial cellulose	Hydrothermal	Antimicrobial materials in meat packaging.	(Ghorbani et al., 2024)
Pineapple peel	Hydrothermal	Electronic security devices	(Vandarkuzhali et al., 2018)

3.1. Biomedical applications of bio-based CQDs

In-vivo and ex-vivo applications require antioxidant and heavy metal-free materials to prevent their detrimental effect. In this regard, bio-based CQDs are applied in detecting and imaging living cells.

3.1.1. Bioimaging

Fluorescent semiconductor nanostructure has gained importance for bio-imaging applications. However, its cytotoxicity effect due to heavy metals, is one of the challenges limiting the use in in-vivo applications. Carbon quantum dots (CQDs) with low toxicity is however desirable in biomedical applications (Akin et al., 2022; Al-Hetty et al., 2023; Ouarrad et al., 2022; X. Zhang et al., 2023). Fruit waste (Kaur & Verma, 2022), cabbage (Alam et al., 2015), and sugarcane bagasse (S. & D., 2016) are some examples of biomass precursors.

Zhang et al. (2025) developed nitrogen and boron doped CQD via using solvothermal method with using citric acid as carbon source, safranine T as nitrogen dopant and 3-aminobenzeneboronic acid as boron source to use in antimicrobial and bioimaging application. Produced CQDs exhibited orange fluorescence emission at 581 nm while have high QY of 41.50%. Moreover, it showed tht excellent antimicrobial activity for *Escherichia coli* (*E. coli*) and *Staphylococcus aureus* (*S. aureus*) (bactericidal rate > 99%) (T. Zhang et al., 2025).

Zhang et al. (2019) produced carbon quantum dots derived from ginkgo leaves for bio-imaging in HeLa cells and detecting Hg^{2+} in lake water. Produced CQDs with great water solubility showed fluorescence quantum yield (FQY) of 11%, great biocompatibility with A549 and Hela cells (Q. Zhang et al., 2019).

Atchudan et al. (2021) prepared CQDs with a QY of 20% by hydrothermal method using banana peels as a carbon source. CQDs have nitrogen and oxygen-containing functional groups and emit intense blue fluorescence under the excitation of 365 nm of UV light. Even though at a high concentration of 200 µgml-1, fabricated CQDs exhibited less toxicity for nematodes. Results showed that fabricated CQDs are suitable for bio-imaging in nematodes thanks to their fluorescence stability and biocompatibility (Atchudan et al., 2021).

Qi et al. (2019) produced Nitrogen-doped carbon quantum dots (N-CQDs) by utilizing rice residue and glycine via the hydrothermal method. Produced N-CQDs demonstrated a fluorescence ranging in wavelength from 420 to 500 nm and can be utilized for Fe^{3+} detection and bio-imaging (Qi et al., 2019).

Shi et al. (2020) synthesized N-doped carbon quantum dots using aminated alkali lignin in order to use in cellular imaging (Y. Shi et al., 2019). Xue et al. (2019) produced lignin-CQDs by utilizing citric acid and ethane diamine via hydrothermal pretreatment to use in bio-imaging implementations (Xue et al., 2019).

The characteristic light absorption of CQDs is generally in the UV region (230–320 nm), and the absorption properties vary depending on the carbon source. CQDs emit blue or green fluorescence against absorption, with PL emission generally redshifted with increasing excitation wavelength. Thus, they can be used in multicolor bio-imaging as the PL of CDs can easily be adjusted by controlling the excitation wavelength (J. Liu et al., 2020).

Thota et al. (2018) synthesized CQDs derived from lemon grass herb that has a high quantum yield of 23 % which can be used in live cell imaging, with a projected implementation in bio-sensing and optoelectronics applications (Thota et al., 2018).

Zhang et al. (2019) synthesized CQDs using alkali lignin, resulting in CQDs with excellent photoluminescence and electrocatalysis qualifications, promising for bio-imaging and metal detection (B. Zhang et al., 2019).

Ren et al. (2019) fabricated CQDs with N doping via pulsed laser ablation with a quantum yield of 32.4%, indicating suitability for bio-imaging applications (Ren et al., 2019).

CQDs have superior antimicrobial activity to microbial strains due to their functional groups. Their antimicrobial properties are determining in human contact applications, drug delivery and bio-imaging (X. Dong et al., 2020).

CQDs are gaining raising interest as fluorescence sensors. CQDs have excellent potential for sensing applications due to their non-toxicity, hydrophilicity, decisive optical qualifications, and surface functional groups (Y. E. Shi et al., 2020).

3.1.2. Biosensor and electrochemical sensor

Pesticides such as organophosphorus, carbamate, organochlorine, pyrethoids, and sulfonylurea are commonly used chemicals in agricultural sectors. These products having positive effect on targeted aim can enter the food chain or the aquatic media. Photoluminescence based carbon quantum dots have gained importance due to detect their infection to the aforementioned area (Gyanjyoti et al., 2023).

Dopamine is vital for human' nervous systems that excess of dopamine (DA) results in schizophrenia whereas lack of DA may trigger depression. Han et al. (2024) prepared N-doped CQD probe from banana peels, orange peels and dragon fruit peels via simple hydrothermal method to detect dopamine. They employed fruit waste as carbon sources and ethylenediamine as nitrogen sources. N-CQDs with concentration of 1300 μL achieved 5.05 μmol L^{-1} of DA in rabbit serum (L. Han et al., 2024). Another study was carried out by Padmapriya et al. (2023) to detect DA by N,P-doped CQDs. They produced N,P-CQD from banana flower bract extract via hydrothermal method. They produced electrochemical sensor with using N,P-CQD and paraffin impregnated graphite that showed great sensitivity and selectivity for DA with a broad linear range of 6.0 μM to 0.1 mM (Padmapriya et al., 2023).

QDOTs from bio-based precursors are extensively used in sensor detection specifically different metal ions. Where ionic liquids (IL) are used as a catalyst to produce CQDs from cellulose, the obtained IL- CQDs have great photostability and detect inorganic mercury in biological products and drugs (B. Wang et al., 2015).

Tao et al. (2022) produced CQDs from wood via hydrothermal method and fabricated composite films with PVA. Produced CQDs/PVA composite film has pH detector feature which can be used to detect the pH change in human sweat during movement, an exciting feature for wearable technologies (X. Tao et al., 2022).

3.1.3. Biomimetic drug delivery systems/carriers

Nanomaterials are currently used in drug delivery, gene therapy, detection and diagnosis, targeted therapy for diagnosis and treatment of cancer (Jin et al., 2020). Bioinspired and biomimetic systems strive for alternatives to conventional nanocarriers preventing implications on the immune system (Sabu et al., 2018). These two terms connect nature and science each other to be applying on the suitable application fields (Johnson et al., 2022).

Even though clinical trials of nanotechnology for cancer diagnosis currently exist, there are some challenges to be addressed. Reliability of the nanotechnology-based cancer diagnosis and acquiring detection results require more attention. Large-scale production of nanoprobes with considerably low-cost, high sensitivity and durability is yet to be achieved. Last, but not least, biodegradable and non-toxic nanoparticles need to be developed especially for in vivo imaging (Y. Zhang et al., 2019).

3.2. Environmental applications of CQDs

In the case of both detecting several metal ions such as Hg^{2+}, Zn^{2+}, Cd^{2+}, Ag^{+}, Au^{3+}, etc. and photocatalytically removing organic and inorganic pollutants, CQDs are a good candidate for the above-mentioned unique properties (Manikandan & Lee, 2022).

3.2.1. Sensing metal ions

Atomic absorption spectrometry, spectrophotometry, inductively coupled plasma mass spectrometry (ICP-MS), and electrochemical methods are used for detecting heavy metal ions. However, they are not suitable for rapid applications due to the need for complicated instrumentation and long sample preparation (C. Wang et al., 2020).

Mercury (Hg^{2+}) is an extremely toxic heavy metal that can accumulate on soil, groundwater, air, sediments even in food chain. Dutta et al. (2025) developed nitrogen doped CQDs via hydrothermal method. Produced CQDs applied as fluorescence probe for Hg^{2+} ion. Its observed limit of detection (LOD) was 4.98 nM that its limit lover than the limit of Environmental Protection Agency (Dutta et al., 2025). Another study was carried out by Dhandapani et al. (2023). They prepared a fluorescence probe for Hg^{2+} ion sensing using chicken feathers as a carbon source by the hydrothermal carbonization method. Obtained CQDs have 77.2% fluorescence carbon yield and are highly sensitive for detecting Hg^{2+} ions (Dhandapani et al., 2023).

Fe^{3+} is considered one of the most common heavy metal pollutants of aqueous environments. Detection of Fe^{+3} is critical to avoid side effects of bioaccumulation. Zhu et al. (2021) have produced green CQD derived from lignin by a two-step method for detecting Fe^{+3} ions. Prepared CQDs showed a high quantum yield of 23.68% with surface functional groups and its nanoprobe exhibited great sensitive reply to Fe^{+3} ions (L. Zhu et al., 2021).

Li et al. (2021) produced fluorescent N-doped carbon dots (NCDs) by pyrolysis method using ethylene diamine (EDA) and citric acid (CA). Environmentally friendly fluorescent probes can detect Fe^{3+} in a wide linear range from 0 to 400 μM (Y. Li et al., 2021).

Qureashi et al. (2021) produced CQDs from lotus stem via hydrothermal method. Lotus stem derived CQDs are reported to have good fluorescence properties and they are promising materials for ferric ions detection in waste-waters (Qureashi et al., 2021).

Woo et al. (2020) prepared a solution with ionic-liquids (IL) and kraft pulp to produce ionic-liquids (IL)-CQDs, then produced cellulose film with CQDs obtained. They emphasized that the cellulose film has detection property for Fe^{3+} with a 2.038 μM detection limit (Woo et al., 2020).

Song et al. (2018) produced CQDs from chitosan via hydrothermal pretreatment and prepared CQDs/AuNPs composite film using gold nanoparticles (AuNPs) with detection property for iodine ions (J. Song et al., 2018).

Wang et al. (2020) synthesized CQDs from orange peel via hydrothermal method. Produced CQDs are proposed as a good alternative for the detection of Fe^{3+} ions, with a recovery rate of 94%-108% for the detection of Fe^{3+} ions in pond water (C. Wang et al., 2020).

Chen et al. (2019) utilized waste tea extract to produce CQDs that can successfully detect CrO_4^{2-}, Fe^{3+} and be used as fluorescent nano-sensors (K. Chen et al., 2019).

Kumar and Gathania (2026) produced CQDs from *Trachyspermum ammi* seed through hydrothermal carbonization to detect copper (Cu^{2+}) ion. Produced CQDs exhibited uniform 3.3 nm spherical particle size. FTIR analysis revealed that obtained CQD is rich in hydroxyl (-OH), carbonyl (C=O), carboxyl (-COOH), and amine ($-NH_2$) functional groups. Developed CQD exhibited excellent selectivity towards Cu^{2+} ions in aqueous phase, which reduced PL intensity to 54% of its initial level, than other metal ions (A. Kumar & Gathania, 2026).

3.2.2. Photocatalytic systems

Photocatalysis is thought as promising solution for using not only individually solar energy but also converting solar energy into chemical energy (F. Zhao et al., 2023). Generating hydrogen and hydrogen peroxide, obtaining high-value added hydrocarbons via converting CO_2 and removal organic pollutants are applied area of CQDs that are used (Yao et al., 2022).

CQDs with great photoinduced charge transfer capability and electric reservoir properties increase the photocatalytic performance desirable for photocatalytic hydrogen production (F. Zhao et al., 2023). Chen et al. (2022) synthesized Ni and N-doped CQDs that can be used as catalysts in hydrogen production due to their high catalytic activity and rapid charge transfer capability (S. Chen et al., 2022).

Surface modification, doping with metallic or non-metallic elements (Sariga et al., 2023) are essential to increase performance of photocatalysis. For example, Han et al. (2020) studied producing excellent quality CQDs via thermal pyrolysis that is a one-pot strategy. In order to remove dyes from the water, surface modification was applied to examine importance of the oxygen species in photocatalysis (W. Han et al., 2020).

Carbon quantum dots have gained attraction in water treatment due to their availability, stability and biocompatibility compared to visible-light-driven photocatalysts. However, complex purification and limited optoelectronic performance are still considered problematic. Ali et al. (2022) studied carbon quantum dots synthesis that have scalable structural design. Produced CQDs altered to amorphous core CQDs (AC-CQDs) through changing synthesis temperature. Reduced graphene oxide was used as environment that AC-CQDs were directly growth above and a tensile-structure electrode was prepared. Thanks to increased photoelectrocatalytic activity, fabricated electrode exhibited 100% removal of effluent dye degradation within 25 min (Ali et al., 2022). Siddharth et al. (2026) produced S,N-enriched CQD from Indian rosewood via microwave methods to examine degradation of aquatic pollutant. Produced S, N-CQDs degraded 15 ppm Malachite Green (MG) at a pH 9, and showed excellent photocatalytic capacity of 95.12% (Siddharth et al., 2026).

In order to treat environmental pollutants, titanium dioxide (TiO_2) is widely employed as a photocatalyst. It possesses wind bandgap that results in less usage of solar energy, requiring its photocatalysts activity (W. Zhao et al., 2021). Zhang et al. (2021) fabricated CQDs from biomass feedstock and used together with TiO_2 in order to develop photocatalytic CO_2 decrement. The CQDs/TiO_2 obtained demonstrated good CO_2 reduction property (J. Zhang et al., 2021).

Due to conjugated π structures, CQDs exhibit transporting and accepting electron greatly. Also, they enable solar radiation absorption from ultraviolet to infrared. Huang et al. (2018) prepared CQDs modified FeOOH nanocomposite to remove NO in the air. Prepared composite exhibited 22% NO removal efficiency and inhibited the formation of final nitrate (Huang et al., 2018).

3.2.3. Wastewater treatment

CQDs have been taken attention to be utilized for removing organic and inorganic pollutants in wastewater. Examples of inorganic pollutants present in wastewater include lead, cadmium, mercury, and copper, as well as organic pollutants including phenols, polycyclic aromatic hydrocarbons (PAHs), and dyes (Khan et al., 2024).

Methylene Blue (MB) is one of organic dyes that are considered among major pollutants in wastewater. Das et al. (2019) produced carbon quantum dots from pear juice with hydrothermal carbonization. The synthesized CQDs show quite good light absorption, superior photocatalytic activity under visible light irradiation, and 99.5% degradation of methylene blue (MB) (Das et al., 2019).

Si et al. (2021) synthesized biobased CQDs from rice straw and prepared CQDs/bismuth oxychloride (BiOCl) with a hydrothermal method that removes 90% of bisphenol A (BPA) under visible light and disinfects BPA in water effectively (Si et al., 2021).

To determine steroid hormones in the lake, wastewater and river, Bianchini et al. (2023) produced silica-supported CQDs applying rice husk ash as precursor through two stage preparation methods. Obtained silica supported CODs presented oxygenated carbon functional groups that enable use in different applications (Bianchini et al., 2023).

Tyagi et al. (2016) fabricated CQDs using lemon peel waste via hydrothermal process and produced nanofibers with TiO_2 and CQDs. The nanofibers produced have good photocatalytic activity for removing methylene blue (MB) dye (Tyagi et al., 2016).

3.2.4. Bioremediation

Sun et al. (2022) fabricated highly water-permeable pervaporation membranes for desalination. They produced amino-embedded carbon quantum dots (ACQDs) by hydrothermal method and produced ACQD-thin film nanocomposite membrane using produced CQDS. The nanocomposite membrane demonstrated an improved water flux of 23.2 $kg.m^2.h^{-1}$ at 70 °C for treating a 10 wt% NaCl solution. Compared to the unmodified thin-film composite membrane, it showed 44% higher performance (J. Sun et al., 2022).

Du et al. (2019) produced nitrogen-doped CQD derived from *p*-phenylenediamine (*p*-PD), exhibiting red emission to detect of the alachlor herbicide in soil (Du et al., 2019).

3.3. Energy applications of CQDs

Energy applications of quantum dots include supercapacitors, photovoltaics including quantum-dye-sensitized solar cells, perovskite solar cells, li-ion batteries, hydrogen evolution reaction (HER), oxygen evolution reaction (OER) (S. Chen et al., 2022; Owen & Brus, 2017; Rasal et al., 2021; Wassweiler et al., 2023).

3.3.1. Electrode

Due to its superior properties such as serving more active sites, making short path for ion/electron diffusion and buffering the mechanical strain during cycling, QDs are a good candidate for producing composite electrode material to enhance electrochemical performance of an electrode (Hei et al., 2023; Sinha & Kar, 2023). CQDs can be used as electrodes and electrolytes for supercapacitors due to their good electrical conductivity and storage qualifications. However, their storage mechanism and production methods must be clearly known to expand their usage in supercapacitors (Permatasari et al., 2021).

Inayat et al. (2023) produced electrode material with CQDs derived from spent tea leaves by hydrothermal oxidation method. Prepared CQDs exhibited crystalline structure and 2-5 nm of size. Based on the electrochemical test, the supercapacitor with CQDS electrode exhibited an outstanding specific capacitance of 302.0 F g^{-1} at a current of 0.5 Ag^{-1}, cyclability with 144.4 F g^{-1} at 20 A g^{-1} after 5000 cycles (Inayat et al., 2023).

Zhuang et al. (2022) synthesized pomelo peel derived CQDs and used NiCo-LDH in order to enhance electrochemical performance of the produced CQDs. Results indicates that NiCo-LDH-CQDs can be used as an electrode materials for supercapacitors (Zhuang et al., 2022).

Nguyen et al. (2022) synthesized CQDs from banana peels via hydrothermal pretreatment, with electrochemical properties suitable for supercapacitor electrodes (T. N. Nguyen et al., 2022). In addition to their electrochemical properties, the porous structure of CQDs allows doping by different atoms, further improving their utilization in energy storage (Thangaraj et al., 2021).

Potassium ion batteries (PIBs) are considered as another promising energy storage device that has a similar working principle with LIBs. PIB are abundant potassium sources, enhancing output voltage and energy density (Y. Chen et al., 2020; R. Guo et al., 2021). Guo et al. (2022) produced CQD@hard carbon (CQDHC) for use as a negative electrode in PIBs. CQDHC prepared using low-step low-temperature pyrolysis methods enhanced potassium adsorption. Prepared electrode demonstrated 97% of high columbic efficiency and long duration, stable charge-discharge reproducibility (Y. Guo et al., 2022).

3.3.2. Optoelectronics

Bio-based CQDs are promising materials in printing applications due to their good optical and fluorescence properties. Ionic-liquids (ILs) are widely used as a solvent for producing CQDs with high quantum yields to be utilized as fluorescent ink. These Ionic-liquids (ILs) provide that CQDs produced have superior stability (B. Wang et al., 2015).

Olmas-Maya et al. (2022) prepared brightness blue CQDs derived from orange peels using a one-step microwave-assisted solvothermal synthesis method. Obtained CQDs were used as impregnation material for mesoporous TiO_2 semiconductor to fabricate thin film using in CQDs-sensitized solar cells as photoanodes (CQDSSC). Results showed that fabricated CQDs/TiO_2 photoanodes enhanced photocatalytic performance and conversion efficiency (Olmos-Moya et al., 2022).

Sharma et al. (2023) produced CQDs self-doped N and Ca from mustard flower via hydrothermal carbonization. Obtained CQDs exhibited yellow-greenish fluorescent and 15% quantum yield. Further, N, Ca co-doped CQDs were used for fabricating biodegradable plastic composites in order to show application in down-conversion light-emitting diodes and optical displays (Sharma et al., 2023).

3.3.3. PV applications

Even though PV panels are available in the commercial market for decades, existing power conversion efficiency is still subject to improvement.

Owing to their affordable-price application in building integrated photovoltaic (BIPVs), recently luminescent solar concentrators (LSCs) are evaluated (Cai et al., 2023). Organic dyes (Q. Li et al., 2023) and semiconductor quantum dots are used in LSCs as emitter material. Wang et al. (2018) synthesized N-doped carbon dots via microwave method in order to embed in polyvinylpyrrolidone (PVP) thin films for manufacturing LSC. Different layered N-CD/PVP thin film based LSCs were compared regarding their optical properties and performance. Different concentrations of N-CD showed that increasing layer number yielded in increasing absorbance intensity. The high power conversion efficiency of 4.97% was obtained with 7 layer N-CDs/PVP thin film based LSCs (Z. Wang et al., 2018).

Riaz and Park (2022) produced nitrogen-rich CQDs-embedded graphitic carbon nitride (CN) nanotubes (CCNTs) to use in quantum dot-sensitized solar cells (QDSCs) as light harvester. Using CCNT resulted in increasing power conversion efficiency of the solar cell, that is higher than individually used material in solar cells (CQD, CN NT, CN-sensitized) (Riaz & Park, 2022).

The incorporation of QDs that have good optical properties into solar cells increases the performance of solar cells by enabling them to use higher energy wavelengths (Farirai et al., 2021). Meng et al. (2017) produced bio-based CQDs from soybean powder by hydrothermal carbonization method and combined with TiO_2. CQDs/TiO_2 used in solar cells showed a maximum dark power conversion efficiency of 7.97% of the solar cells (Meng et al., 2017).

Gomes et al. (2019) synthesized CQDs using chitosan via hydrothermal treatment, which has the potential to be used in solar cell applications with a quantum efficiency of 17.1% (Gomes et al., 2019). Juang et al. (2018) synthesized bamboo-based CQDs that can be used as cathode exchanger layers in PV applications, due to its ability to increase electron mobility (Juang et al., 2018).

To achieve high performance in perovskite-based devices, perovskite structural and surface morphology optimization, including grain structure, defects, compactness, and surface affinity/hydrophobicity, is critical. Song et al. (2020) developed a combination of pulsed laser technology and CQDs into perovskite to enhance its carrier transportation in the film through passivating grain. Results showed that developed engineering material is highly promising under harsh conditions (C. Song et al., 2020).

3.4. Food applications of CQDs

Active packaging that comprise of addition antibacterial agents and antioxidants to packaging materials are of vital importance in order to enhance both safety and shelf-life of foods (Ezati et al., 2022). To provide these, biodegradable, anti-oxidant, anti-ultraviolet, antibacterial and biocompatible films are developed for packaging purposes (Deepika et al., 2023).

3.4.1. CD-based sensors in the area of food safety

Antibacterial properties of CQDs are of interest in the food packaging industry. CQDs could be used as polymer matrices, producing composite films with good mechanical properties and UV protection, adding to antibacterial quality (Roy et al., 2021).

Patil et al. (2020) synthesized biobased food packaging films using waste tea residue CQDs and PVA via solvent casting method. The composite film produced with waste tea residue-CDs tested as a packaging material for grapes and the film can block 100% of UV light for 230−280 nm and 20−60% of UV light for 315−400 nm (Patil et al., 2020).

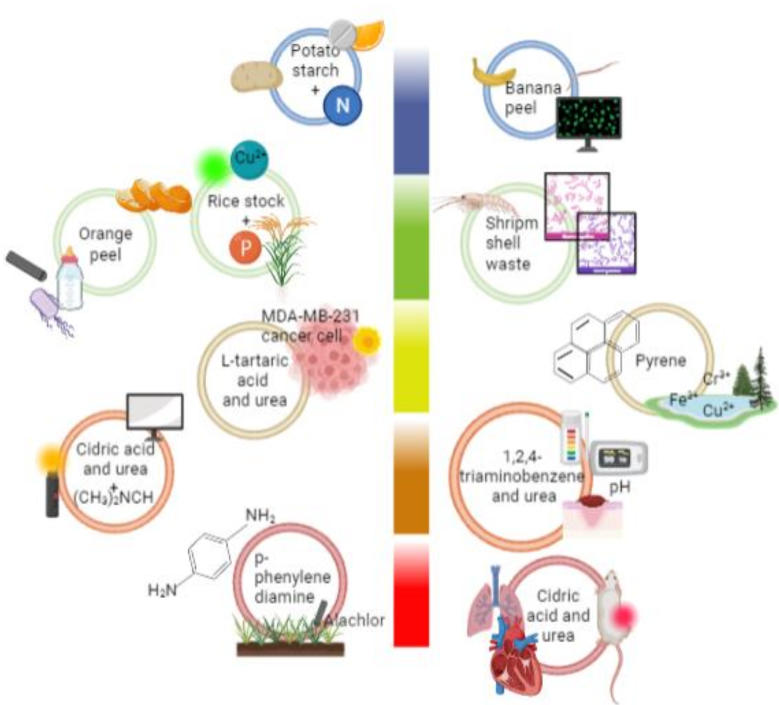
The antioxidant properties of CQD due to their surface hydroxyl groups have also brought up its potential use in food packaging applications (W. Zhang et al., 2018). Khoshalampour et al. (2023) produced bioactive gelatin film to use in food packaging. CQDs derived from grape leaves were introduced to Dialdehyde Persian gum (PE) to manufacture nanocomposites. The oxidized PE/gelatin film showed decreasing effect on UV transfer while enhancing the antioxidant activity almost four times and exhibiting antibacterial activity (Khoshkalampour et al., 2023).

Cao et al. (2022) fabricated a fluorescent detection probe from natural red beet pigment to detect tetracycline (TET) residue that is required to be removed from food to prevent its harmful health effect. The red beet pigment carbon dots showed great detection against TET in animal derived foods such as milk, eggs and chicken (Cao et al., 2022).

3.5. New Era

In light of all conducted research, it should be pointed out that thorough experimental approach is crucial to expand CQD applications by enhancing their performance. Ongoing efforts to expand their utilization give way to CQDs with superior properties, rendered viable in a wide range of applications. CQDs obtained from different carbon sources have different fluorescent wavelengths. Figure 3 shows CQDs derived from different precursors and their respective application fields based on their fluorescent wavelength.

Figure 3 Different precursors of carbon quantum dots and their application fields



The superior electrical, solubility, bandgap tunability and physicochemical properties of CQDs enable them to be preferred in photovoltaic devices, light-emitting diodes and supercapacitors. In addition to current applications, new and developing opportunities for CQDs are yet to be discovered. Liu et al. (2023) fabricated aloe peel-derived CQDs via anaerobic co-digestion. CQDs derived from aloe peel used as accelerators in anaerobic co-digestion systems improved the system performance by improving electron transfer in the process (L. Liu et al., 2023).

Sun et al. (2017) prepared CD-NTf_2 with high chemical stability. CD-NTf_2 has a long-term writing feature due to its non-volatile content and it can be used as a writing ink (X. Sun et al., 2017).

Wang et al. (2022) produced carbon dots from starch to use as additive to fingerprint powder for latent fingerprint (LFP) imaging. Produced CDs enhanced the photoluminescence quantum yield of fingerprint powder up to 41.75%. LFP systems demonstrated high visualizing definition and contrast under varied conditions (X. Wang et al., 2022).

CQDs with high functionalizability can be used as green inhibitors to prevent acid corrosion of metals. Yang et al. (2019) synthesized imidazole ionic liquids (IL) and citric acid-based carbon dots as green inhibitors to improve the corrosion resistance of steel. IL-functionalized citric acid based CQDs provided protection against to HCl and NaCl corrosion (Yang et al., 2019).

Han et al. (2019) produced CQDs with 26.9% N and S co-doped to manufacture a fluorescent, gradually increasing/decreasing temperature sensor in the temperature range of 5–70 °C. N and S doped CQDs are reported to enable the production of sensors with more sensitive response (Z. Han et al., 2019).

Guo et al. (2024) prepared bell pepper derived nitrogen-doped carbon dots (CQDs) with hydrothermal carbonization which have high quantum yield of 23.2%. They emphasized that CQDs obtained can be used as a pH-modulated fluorescence switching nano-sensor to detect 4-NP from 0.054 to 68 μM with low detection limit (LOD, 54 nM). Consequently, they demonstrated that bell pepper derived nitrogen-doped carbon dots (CQDs) have prospective applications for on-site 4-NP monitoring in food (G. Guo et al., 2024).

Zhang et al. (2024) utilized Chinese herb mulberry and $MgCl_2 \cdot 6H_2O$ as the magnesium dopant to produce Mg-doped CQDs with hydrothermal carbonization. The results show that Mg-doped CQDs have potential to use as osteoblast gene markers hence, they will become promising materials in bone repair by combining them with scaffold materials (Q. Zhang et al., 2024).

Praseetha et al. (2021) produced a chronic wounds gel with combination of aloe vera gel and carbon quantum dots that derived from beet root extract. Produced CQDs showed antibacterial properties and tissue biocompatibility (Praseetha et al., 2021).

Mei et al. (2024) prepared biobased carbon quantum dots (CQDs) with utilizing okra-derived and manganese dioxide nanosheets (MnO_2 NSs). They emphasized that the Fluorescence intensities of okra-derived CQDs are enhanced due to the oxidase-mimetic activity of MnO_2 NSs. They concluded that, the okra-derived CQDs produced have potential application for routine Dichlorvos (DDVP) monitoring in foods (Mei et al., 2024).

Ghorbani et al. (2024) utilized antimicrobial bacterial cellulose (BC) membranes and CQDs together in order to enhance the shelf life of minced beef. The results show that BC-CQDs have better microbial properties than BC membranes. They concluded that, BC-CQDs demonstrated that important reduction (4.7 log10CFU/g) in Escherichia coli counts by the end of storage hence, BC-CQDs will utilize as antimicrobial materials in meat packaging (Ghorbani et al., 2024).

Surendran et al. (2020) fabricated CQDs using orange waste peel for use in optically switched photonic devices (Surendran et al., 2020). Vandarkuzhali et al. (2018) fabricated CQDs from pineapple peel and used them in electronic security devices (Vandarkuzhali et al., 2018). Park et al. (2020) synthesized CQDs from waste paper and used them to make anti-counterfeiting inks (Park et al., 2020).

CQDs are preferred to increase power conversion efficiency in solar cell applications due to their wide light absorption spectrum extending to the visible area. CQDs can be used as a substitute for the electron transport layer in solar cells or as an additive material to synthetic materials such as TiO_2 used in the electron transport layer, thanks to their low toxicity and good electron removal capacity (P. Kumar et al., 2022).

The carboxylic, hydroxyl and amino groups of CQDs make the contacts between the layers stronger, thus resulting in improved optoelectronic properties. Zhang et al. (2017) stated that it is possible to produce solar cells with enhanced photo-catalytic activity under visible irradiation as a result of utilizing the N-doped CQDs (NCQDs) and TiO_2 (Magesh et al., 2022).

Compared with materials containing organometallic complexes (metal-containing) and pure organic compounds (metal-free) with room temperature phosphorescence (RTP), CQDs with RTP offer an alternative for applications due to their simple design and low cost. Therefore, they can be utilized to facilitate multi-level information security. With further improvement of the efficiency and stability of CQD-based materials used in anti-fraud and data security applications, it will be possible to use CQDs more widely in security encryption in the future (S. Tao et al., 2018).

These studies are among the examples of the use of CQDs in different application areas and encourage researchers to fully explore the remarkable properties of CQDs that are preferred in many advanced applications. The increasingly well-understood properties of these new opportunities, biobased CQDs, play an important role in paving the way for their use in many other application areas.

Increasing awareness of biobased CQDs will not only serve a broader range of applications but will also present their potential for production through green synthesis of carbon quantum dots, a class of carbon-based nanomaterials that has attracted considerable attention. Introducing the production of carbon quantum dots through green synthesis will lead to an increase in research studies on the use and development of these methods in the production of carbon-based nanomaterials.

4. Conclusion and Future Projections

CQDs, which are among carbon-based nanomaterials, have gained popularity in the last decade. CQDs can be produced by different methods as an alternative to commercial market products, with potential for application in various fields.

In view of sustainable development, utilizing biomass sources as feedstock for producing alternative commercial materials, especially CQDs, is a step towards conserving limited and rare sources. Various biomass feedstocks are used as carbon sources for a wide range of applications including biomedical, electrochemical, and optical applications that have detailed subsections such as biosensoring, bioimaging, drug delivery systems, food packaging, supercapacitors and metal ion detection. Reviewed research study results show that the superior electrical conductivity, quantum yield, photoluminescence, and cyclic stability of biomass-derived CQDs have attracted much interest from researchers. Furthermore, besides the biocompatible structure of biobased CQDs, good antibacterial and antioxidant properties have been noticed. Ongoing research suggests their emerging applications such as wearable technologies or flourescent ink printing. Consequently, the researches imply that the sensoring and fluorescence properties could be enhanced by combining with various materials like PVA, polymer, etc. and doping with different elements such as N, B, S. In order to expand their utilization in niche fields, the utilization of renewable resources in the combination and doping processes should be increased.

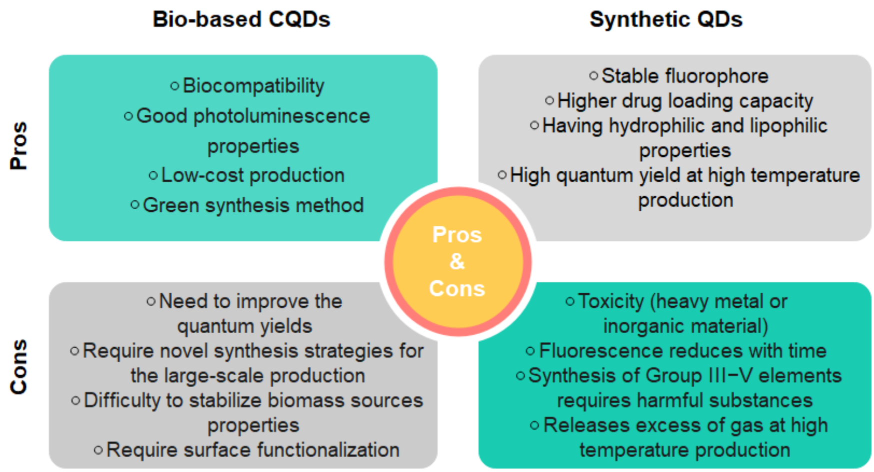
Biomass is a renewable source in this regard; serving as feedstock in CQD production. They mostly accumulate heavy metals within their roots and remediate the polluted soil. Hence, it could be an alternative way of using hyperaccumulating plant species that have affinity for Zn, Cd, Ni, As, Co, and Mn to decrease both the earth metal usage for producing QDs and the heavy metal content in the soil.

However, evaluating the properties of these sources and choosing the most suitable one for the desired application needs to be investigated by researchers. Identification of adjustable properties, such as functional groups and wavelengths, by selecting the most appropriate fabrication method and choosing suitable biomass sources will enable QDs to be used not only as scientific research subjects but also as commercial materials. Within the open commercialization of biomass sources, derived-CQDs will contribute to conserving rare elements and also preventing waste production, which will consequently serve the sustainable development principle.

All of the applications described in the above section of CQDs have been scientifically researched and have gradually started to be applied in real life, specifically in display and biomedical applications. It is expected that they will have potential usage in aerospace applications, aviation, and automotive sectors.

The advantages and disadvantages of biobased CQDs, which have the potential to be used in different application areas due to their promising properties, are presented in Figure 4 in comparison with synthetic QDs currently used in the industry.

Figure 4 Pros&Cons of Bio-based CQDs and Synthetic QDs



To promote their implementation, large-scale production of CQDs is an indisputable challenge requiring action for infrastructure. The competitive qualifications of CQDs shed light on the need to develop new synthesis strategies to extend their usage in current and future applications. The combination of bottom-up and top-down methods is among the new synthesis strategies that are used to improve the quantum yields and luminescence properties of CQDs. These new and novel synthesis strategies enable the large-scale production of biomass-derived CQDs by improving the product yield of the CQDs. CQDs are brought to commercial scale production from the research level through large-scale production. Hence, the biomass-derived CQDs could have become economically viable in the market for carbon-based products. While CQDs have advanced implementations, financial support from state and private sectors is still needed to proceed with the research to secure a permanent place in the market.

Even if some research applications (the Department of Energy's Oak Ridge National Laboratory) and some start-ups and new player companies have attempted large-scale manufacturing, it still needs initiative to promote more companies and research centers for this purpose. Furthermore, companies that engage in biorefinery can be supported and promoted through national grants for integrating the production of CQDs into their current manufacturing operations. It can be one more step to approach both sustainable development and the circular economy by recognizing that CQDs should take place at the center of our common future.

In this way, it will be possible to bring carbon-based nanomaterials, which are among the materials of the future, into the economy in a more environmentally friendly and low-cost way, hence, innovative approaches can be put forward for the development of carbon-based materials, which play an important role in the development of material science.

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CHAPTER 3

GREEN AND SUSTAINABLE TECHNOLOGIES FOR LITHIUM-ION BATTERY RECYCLING

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Introduction

The market for motor cars in the future will be driven by electric vehicles (EVs). This kind of vehicle is expected to account for roughly half of all vehicle sales worldwide (100 million) in 2035 (Prasetyo et al., 2025). Recently, lithium-ion batteries (LIBs) have been gained attention due to their extensive utilization in energy storage power stations and electric vehicles. Hence, the growing adoption of electric vehicles has led to a significant rise in the demand for LIBs. As LIBs have a finite operational lifespan, the generation of end-of-life batteries is also continuously increasing (Zhu et al., 2024). The high demand for LIBs in market has increased the requirement of critical raw materials (CRM) especially cobalt (Co), lithium (Li), nickel (Ni), manganese (Mn), aluminum (Al) and copper (Cu) (Vauloup et al., 2026). The demand for lithium is expected to rise from 200,000 tonnes per year to 1.4 million tonnes by 2040, according to the International Energy Agency (IEA) [3]. Similarly, by 2040, demand for copper, nickel, and cobalt is

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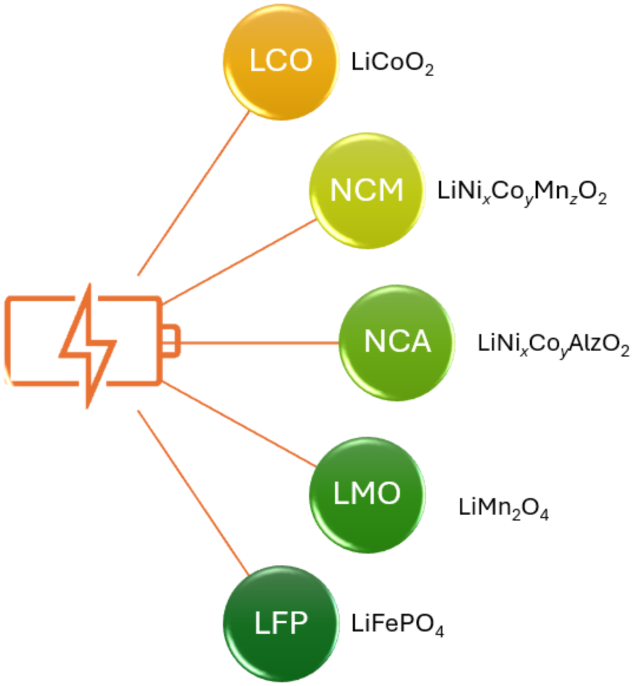
predicted to increase to 150%, 210%, and 220% of 2023 levels, respectively (Deberdt et al., 2025). By recycling secondary metallic resources, recycling might significantly contribute to the circular economy and the general sustainability of future LIBs. According to reports, recycling and reusing important metals like copper and nickel from old LIBs might limit the extraction of metals from virgin mineral sources and conserve 51.3% of natural resources (Biswal & Balasubramanian, 2023).

Cathode, anode, separator and electrolyte are four main components of LiBs (Biswal et al., 2024). Anode material basically consists of graphite whereas a variety of cathode chemistries are utilized, including NCA ($LiNixCoyAlzO_2$), LFP ($LiFePO_4$), NMC ($LiNixCoyMnzO_2$), LCO ($LixCoO_2$), and LMO ($LiMn_2O_4$) (Meshram et al., 2025; Mušović et al., 2025). Cathodes are essential parts of LIBs that have high effect on their performance. Based on specific application, their composition can change (Kovačević et al., 2024). The separator, typically fabricated from polypropylene or polyethylene, serves as an insulating barrier between the electrodes to prevent internal short circuits (González & Pérez Rodríguez, 2025). The electrolyte, usually consisting of lithium salts such as $LiClO_4$, $LiBF_4$, $LiPF_6$ dissolved in non-aqueous organic solvents, facilitates ion transport between the cathode and anode, enabling the electrochemical reactions necessary for energy storage and power generation. Anode is fabricated from graphite and carbonaceous materials that are placed on copper foil as current collector (J. Zhang & Azimi, 2022). Figure 1 exhibits various LiBs series.

Figure 1. Lithium battery series (generated from (Fan et al., 2020))



Cathode material of Li-ion batteries has been valuable due to having cobalt, nickel, copper and lithium to recover. Thanks to latest EU Battery Directive, it was determined that the overall weight percentage recycling efficiency of lithium-ion batteries must be at least 90% by 2030. However, it is not possible to reach this target without recovering the less valuable parts including electrolyte and separator (Yang et al., 2025). This chapter provides a comprehensive review of green and sustainable technologies for lithium-ion battery recycling. Section 2 reviews lithium-ion battery recycling methods and follows with green technologies including bioleaching, organic acid leaching, deep eutectic solvents, ionic liquid, and supercritical CO_2 extraction. Section 3 addresses the advantages and challenges of green recycling techniques while Section 4 close the chapter with conclusion and future prospects.

Lithium-ion battery recycling methods

Pyrometallurgy, hydrometallurgy and direct recycling are main recycling methods for lithium ion batteries (Sun et al., 2024; Yu et al., 2024). Pyrometallurgy needs high temperature and generates gaseous side-products such as Fluorine, dioxins and furans that is not desired (J. Wang et al., 2023). Even though this method applied in various industries to recover of Li, CO, Ni, Fe, Cu and etc., Li recovery amount is considerably low (Uppin et al., 2026).

Hydrometallurgical process employs strong inorganic acid including HCI, H_2SO_4, and HNO_3 to recover valuable precursors from spent LIBs. However, this process generates pollutant which are harmful to the environment (Nayaka et al., 2019). Acid concentrations and type, temperature, solid-to-liquid ratio, time and added reducing agents' impact on leaching efficiency. Even though it has high recovery rate and easily leach all metals, its main problem is producing harmful gases including SO_3, CI_2, Nox and residual harmful substances (Roshanfar et al., 2024).

The direct recycling approach focuses on restoring the electrochemical performance of spent LIB electrode materials by reactivating and regenerating the active materials. Unlike conventional recycling methods, it avoids dismantling the materials into their constituent elements and subsequently resynthesizing them, thereby preserving their original structure and functionality. The advancement of direct recycling technologies remains limited at present because of the rapid evolution of diverse cathode materials and newly emerging cathode chemistries (Y. Wang et al., 2025).

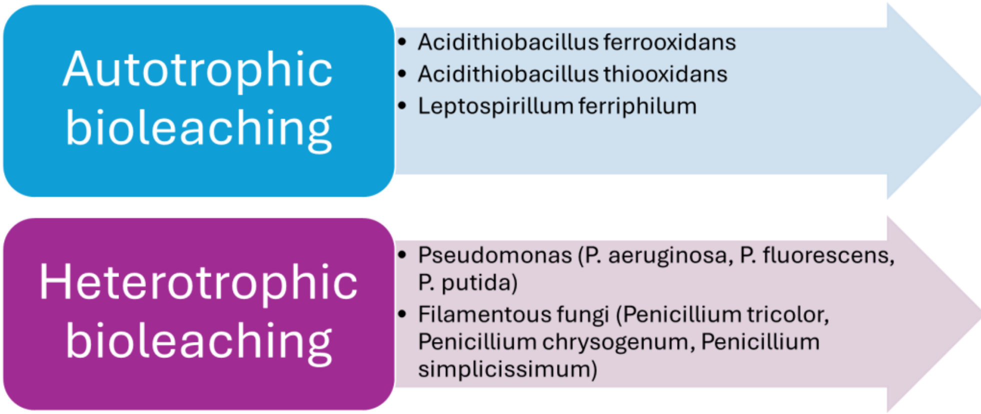
Recently, green and more sustainable recycling methods have been proposed and have begun to be investigated to mitigate drawbacks of conventional processes. Bioleaching, organic acid leaching, ILs utilization, deep eutectic solvents (DESs), supercritical CO_2 extraction ($ScCO_2$) methods are accounted for new approach to recovery valuable metals from spent LIBs. In the following section each of these methods are examined in detail.

Bioleaching

In biohydrometallurgical processes, microorganisms are used in the leaching process to selectively dissolve the system's desired components into soluble compounds. During their development phase, these microorganisms generate acids, and their leaching process is comparable to hydrometallurgy. Temperature, pH, solid/liquid ratio, redox potential, oxygen and carbon dioxide quantity, pulp density, and nutrient concentration are essential parameters that effect on bioleaching (Roy et al., 2021).

Based on their nutritional and energy sources, microorganisms are categorized into diverse groups to leach metal biologically. Mainly bioleaching is divided into two groups which are namely autotrophic leaching and heterotrophic leaching. In autotrophic leaching, chemolithotrophic organisms consume atmospheric carbon dioxide as carbon source and inorganic substances including ferrous iron and sulfur as an energy source (González & Pérez Rodríguez, 2025). They generate metabolites ferric ions or sulfuric acid that play as oxidizing agents to dissolve metals from spent LIBs (Roy et al., 2023). In heterotrophic leaching, heterotrophic bacteria and fungi play active role. They utilize carbon to produce organic acids to leach metals (González & Pérez Rodríguez, 2025). Fungi have a shorter lag phase and a quicker leaching rate than bacteria, making them superior to bacteria for a variety of hazardous metals. Additionally, fungus can grow up in wastes that consume both acids and alkalines (Biswal & Balasubramanian, 2023). Figure 2 exhibits microorganisms in autotrophic and heterotrophic leaching.

Figure 2. Autotrophic and heterotrophic leaching and their microorganisms (generated from (González & Pérez Rodríguez, 2025))



Using microorganisms like fungi, chemolithotrophic bacteria, and acidophilic bacteria as leaching agents, bioleaching is a bio-hydrometallurgy technique that removes precious metals from a substrate (Lo Sardo et al., 2025). These microbes create metabolites in the leaching media that aid in the recovery of metals by using sulfur and ferrous ions as energy sources. Bioleaching offers several advantages over conventional metal recovery techniques, including total metal recovery, ease of use, affordability, and reduced energy usage. Bioleaching is an appealing approach for metal recovery since it doesn't require harsh conditions or specific industrial equipment, which is one of its major advantages (Zanoletti et al., 2024). However, the process inherently includes some limitations such as specific temperature, pH, nutrient conditions which are essential for growth of microorganisms and leaching progress. The process's slow kinetics could be a drawback for its commercia application (Cong et al., 2026).

Fritze and Hedrich (2026) have investigated spent medium bioleaching for lithium recovery from LFP black mass using both floated and unfloated materials. Spent medium was first produced by

Acidithiobacillus thiooxidans at pH 1.0, then applied for leaching. Process parameters, including H_2O_2 addition, were optimized, achieving up to 85% lithium recovery (unfloated) and 88% (floated). A hybrid approach with low H_2SO_4 concentration further increased recovery to 91%. Results demonstrate that bioleaching is an effective method for LFP recycling at higher solid loads with low acid use and short processing times (Fritze & Hedrich, 2025).

Ilyas et al (2024) have investigated bioleaching of LCO cathode material from spent Li-ion batteries using *Aspergillus niger*, which produces organic acids to dissolve metals. Both one-step and two-step approaches were evaluated to assess microbial contact effects and metal toxicity. One-step bioleaching achieved a higher lithium recovery (96%), while two-step bioleaching increased the dissolution rate but resulted in a slightly lower yield (94%). Both methods were highly selective for lithium, retaining over 99.3% of cobalt in the residue (Ilyas et al., 2024).

Graphite is a non-substitute material that is used in LIBs as anode material. Among the various graphite types, graphite anode or spherical graphite are only materials for using in LIBs. Due to its high-cost manufacturing process, it needs to be recovery and reused. Roy et al (2023) have worked on graphite recycling using bioleaching and following mild acid leaching to remove iron salts in bioleaching residue. 99.78% of pure graphite was obtained (Jegan Roy et al., 2023).

Organic Acid Leaching

Recently organic acids have taken attention due to their more environmentally friendly nature compared to inorganic acid. In recent years, wide variety of organic acids including citric acid, maleic acid, tartaric acid, glycine (Nayaka et al., 2019), acetic acid (Setiawan et al., 2019), and lactic acid (Santhosh & Nayaka, 2021) have been reported for leaching of cathode materials.

Segura-Bailon et al (2025) have worked on extracting lithium from Nickel-Manganese-Cobalt batteries through using citric and oxalic acid as leaching agents. Even though both ions were good for dissolving lithium, oxalate demonstrated a whole lithium dissolution in the condition of 1 M oxalic, 50g/L, 60 °C, min 60 min with milled sample (Segura-Bailón et al., 2025).

Uppin et al (2026) have applied microwave assisted recovery of Co, Ni, Mn, and Li from cathodes of spent LIBs using organic acid leaching and precipitation. Tartaric acid (TA) and gallic acid (GA) were used as a chelating agent and a reducing agent, respectively. Based on optimized conditions, 0.1 M TA, 0.02 M GA with solid-to-liquid ratio of 2g/L and 5 min microwave irradiation, 97.5% Co, 98.6% Ni, 96.8% Mn, and 99.5% Li successfully leached. Using the solid-state method, $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ was synthesized by obtained metal precursors (Uppin et al., 2026).

Prasetyo et al (2025) have utilized the low concentration of monosodium glutamate to recover Co and Li from spent battery cathode. Under leaching conditions, more than 95% of Co and Li may be dissolved.MSG 0.1 M (18 g/L), pH 5, pulp density 20 g/L, room temperature, leaching duration 6 hours, and sodium sulfite 0.5 M as a reductant. It is reported pH has critical role on leaching efficiency that the most suitable range is pH 4-5. A pH of less than 4 produces neutral and cationic glutamate species that have no affinity for cobalt ions, but a pH of more than 6 causes $Co(OH)_2$ to deactivate the surface (Prasetyo et al., 2025).

Recently, biomass derived reducing agents have taken attention thanks to their combined efficiency with acid leachate and contributing to circular economy. Orange peel, tea waste, grapes seeds, bagasse pith, inkgo biloba, and grape skin can be given to biomass derived reducing agents (Jungi et al., 2025).

Even though organic acids high reducing property, in some situations it is necessary to add another reducing agents like H_2O_2, glucose, $Na_2S_2O_3$ (Morina et al., 2023). Among them, H_2O_2 is widely used reductant agent during leaching process. To mitigate its drawbacks including being unstable and decomposing easily, natural based reductants have been recently proposed. Wang et al (2025) used grape pomace as an organic reductant instead of H_2O_2 to recover valuable materials from spent LIBs. High recovery efficiencies (>98%) for lithium, cobalt, manganese, and nickel were achieved from NCM cathode materials, and regenerated NCM523 cathodes showed promising electrochemical performance. The results demonstrate the potential of this method for large-scale and next-generation battery material recycling (Y. Wang et al., 2025).

Wang et al (2022) employed acetic acid and H_2O_2 as leaching agents to recover Li, Co, Mn, and Al from cathode and anode material of spent LIBs. Acetic acid concentration, solid-to-liquid ratio, temperature, time and H_2O_2 concentration were optimized to reach high leaching efficiency. The leaching rates of Li, Co, Mn, and Al were obtained as 98.56%, 94.61%, 96.39%, 97.97%, and 94.7%, respectively for the conditions of 2 M acetic acid, 4.0 vol.% H_2O_2, 20 g/L, and 70 °C for 40 min (K. Wang, Zhang, & Luo, 2022).

Another study was carried out by Nayaka et al (2019). They employed the ascorbid acid as reducing agent, and nitrilotriacetic acid (NTA) and adipic acid (AA) as gelating agents to leach Li and Co from spent $LiCoO_2$ battery. Two leaching and reducing agent combination were investigated; NTA - ascorbic acid (N-A), and adipic acid – ascorbic acid (A-A) at 80 °C. Results showed that A-A combination showed higher leaching efficiency than the combination of N-A. Leaching of about 79% Co and 87% Li ions was seen in just one hour, and after six hours, it was 85% and 92% for Co and Li ions, respectively, for an A–A mixture (Nayaka et al., 2019).

Setiawan et al (2019) investigated utilizing acetic acid to recover valuable materials from spent LIBs and kinetic modelling of progress. They applied shrinking core model as mathematical model to better understand kinetics during leaching process. Different process factors including pH, temperature, H_2O_2 concentration, and the solid-to-liquid (S/L) ratio were examined. Results showed that temperature is the main factor that impact on Li and Co recovery rate. The highest Li recovery of 87.95% was obtained in the condition of pH 2.09 and 2.8 M acetic acid usage while Co recovery stayed less than Li. Increase in temperature resulted in enhance Li recovery due to its endothermic nature while decrease on Co recovery owing to its exothermic nature (Setiawan et al., 2019).

Santhosh and Nayaka (2021) examined lactic acid usage to recover Li and Co from spent $LiCoO_2$ cathode active material. Various concentrations of lactic acid (0.1-0.5 M) with ascorbic acid (0.02 M) were used for dissolution process. Under the optimum conditions of 0.5 M of lactic acid, 0.02 M of ascorbic acid, 90 C, 6 h and 2 g/l of S/L, The highest Li and Co recovery rate of 99% and 98% was achieved. This study showed that it is possible to recovery 98-99% of critical minerals from spent LIBs through the method with low-cost, simple and environmentally friendly (Santhosh & Nayaka, 2021).

Deep Eutectic Solvents (DESs)

Solvometallurgy employs greener alternatives in contrast to hydrometallurgy that are commonly use aqueous and strong chemicals (Amphlett et al., 2026).

Deep eutectic solvents (DESs) and ionic liquids (ILs) are considered green solvents due to their tunable physicochemical properties, which enable their use in a wide range of applications. Compared to volatile organic compounds (VOCs), they offer many advantages (Chen & Mu, 2021). They offer unique properties including low toxicity, biodegradability, selectivity, and tunable synthesis (J. Wang et al., 2023). Therefore, they have attracted considerable attention in battery recycling applications for the recovery of valuable metals, current collectors, and graphite (Kityk et al., 2024). A hydrogen bond acceptor (HBA) and a hydrogen bond donor (HBD) are incorporated to create DESs, which have a lower melting point than their constituent parts (Svärd et al., 2024). Various DESs systems including ethaline DES (chlorine chloride (ChCI): ethylene glycol (EG) (1:2)) (Tran et al., 2019), poly (ethylene glycol) 200 (PEG 200): thiourea (2:1) (Chen et al., 2020), ChCl:urea (1:2) (S. Wang et al., 2020), *p*-toluenesulfonic acid (PTSA):H_2O:ChCl (1:1:1) (Roldán-Ruiz et al., 2020) have been reported to recovery metals from spent LIBs.

Ye et al. (2025) investigated metals recovery from ternary cathode materials (MNC) using low-viscosity DES. A tetramethylammonium chloride–aconitic acid (TMA–AC)-based deep eutectic solvent was newly formulated and synthesized for the recovery of metals from NCM333 cathode materials. The leaching process was conducted under moderate conditions at 90 °C, while ethanol was employed as a precipitating agent to facilitate both selective metal separation and DES recovery. The results revealed leaching efficiencies above 99% for Li, Ni, Co, and Mn. In addition, ethanol-assisted regulation of the metal coordination environment enabled the simultaneous coprecipitation of Ni, Co, and Mn, effective lithium separation, and straightforward regeneration and reuse of the DES after simple processing (Ye et al., 2025).

Cheng et al (2025) prepared water-based choline chloride-oxalic acid (ChCI-OA,) DESs to recover Li and Co from spent LIB. With the help of DES, lithium oxalate ($Li_2C_2O_4$) instantly precipitated, and the addition of water produced $CoC_2O_4 \cdot 2H_2O$ from the leftover Co-rich leachate. 91.2% of Li and 94.6% of Co were recovered successfully at 100 °C, 2 hour and 5 mg/ml of solid-to-liquid ratio. H2O-based DES helped to reduce viscosity of ChCI-OA and enhanced the leaching efficiency. However, varying H_2O content in DES showed that when molar ratio of H_2O is 1, both Li and Co precipitate together. Increasing or decreasing of it in DESs resulted in deterioration of leaching efficiency either Li or Co. Additionally, it was stated that prepared DES can be reused till 5 times without decrease in leaching efficiency (Cheng et al., 2025).

Wen et al (2024) employed a ternary deep eutectic solvent consisting of choline chloride, malonic acid and 2-pyrrolidone to separate and leach $LiCoO_2$ cathode active material simultaneously. Prepared DESs achieved high separation efficiency more than 98% for cathode materials. Moreover, Li and Co leaching efficiency obtained >96% while less than 4% for aluminum (Al). Malonic acid aided to reduce Co^{+3} in $LiCoO_2$ to Co^{+2}. It was reported that after multiple cycle, DES exhibited outstanding performance based on solvent reusability test (Wen et al., 2024).

Another type of low cost, environmentally friendly and recyclable DESs was prepared with caprolactam (CPL), urea (UR), and formic acid (FA) by Cao et al (2023) to recovery Li and Co from spent LCO cathode material. They especially chosen three components due to their unique properties; FA has strong reducing capacity, and it is considered as HBD in many DESs, UR is one of ideal carrier for coordination of cobalt ions, and CPL plays a stabilator role in the reaction that is not consumed and not coordinate with metal ions. The findings show that Li+ ion leaching efficiency is higher than 99%. At the bottom of DESs, a purple precipitate known as $NH_4Co(HCOO)_3$ was created when FA reduced Co^{3+} ions. Thanks to addition of little amount of FA and UR, more than 20 times cyclic leaching were performed (Cao et al., 2023).

Lu et al (2022) carried out metal extraction from spent LIBs using DESs which is mixture of ChCI (HBA) and various HDBs including malonic acid (MAL), malic acid (MA), ρ-toluenesulfonic acid (PTSA), oxalic acid (OA), propionic acid (PR), citric acid (CA), ethylene glycol (EG), polyethylene glycol (PEG), and urea (AR). The mixture of ChCI and malonic acid enhanced the performance of DES, yielding excellent leaching efficiency. The leaching efficiency of Co and Li was obtained as 98.61% and 98.78%, respectively at 100 °C. Utilized DES played both leachate and reducing agents. It was stated that temperature had an important role in leaching material. Various DESs showed different leaching efficiency with temperature changes (Lu et al., 2022).

Reusability of DESs is very important to minimize additional solvent usage. Another important point is their market price. Luo et al (2023) reported that the market price of oxalic acid and choline chloride are cheaper than most ILs. Additionally, being naturally degradable and having lower environmentally impact move them forward from inorganic acid (Luo et al., 2023).

Ionic Liquids

Ionic liquids (ILs) are composed of cations and anions linked through ionic interactions and exist in the liquid state at or near room temperature. In addition to ionic interactions, ionic liquids (ILs) also involve other intermolecular forces, including hydrogen bonding and van der Waals interactions. ILs are considered unique solvents because they combine the fluidity of molecular liquids with the ionic nature of ionic compounds (Chen & Mu, 2021). ILs provide unique properties including very little vapor pressure, being highly thermally stable and having a broad range of synthetic adaptability (Hu et al., 2024).

Hu et al (2024) utilized imidazolium glycol ([DHPMIm]Cl) as ILs to extract metals from spent LCO cathode material. ILs enhanced the reducing Co+3 into soluble Co+2 forms without using acid and reductant. At 120 °C and 20 h, leaching efficiency was obtained for Li and Co as 100% and 99.62%, respectively. It was reported that this method provides high efficiency for Li over 99% and 80-90% for other metals. During the leaching process, any toxic gas emissions was not produced (Hu et al., 2024).

Morina et al (2023) investigated Li and Co recovery from LCO cathode material using 3-methyl-1-octylimidazolium thenoyltrifluoroacetone, Omim-TTA, as ionic liquid. In order to enhance separating selectively Li, EDTA was added to the aqueous phase. It aided to stabilize Co ions. Results showed that more than 70% of Li was recovered and diversified from Co (Morina et al., 2023).

Zhang et al (2023) employed a novel imidazolium IL with Tributyl phosphate (TBP) extractant to recover Li from spent LIBs (Zheng et al., 2022). Experiments were conducted to solvent of NMC type cathode material with high metal concentration that was obtained after leaching with sulfuric acid and H_2O_2. Under these conditions; 20%:80% of IL:TBP IL concentration, beginning pH of 5, 30 min, yielded high Li efficiency of 88.7% at one stage extraction and 92.5% at three stages cross-flow extraction. Developed method showed high selectivity toward Li while the transfer of other valuable metals (Ni, Mn, Co) to the organic phase remains below 4% (Zheng et al., 2022).

Supercritical CO2 extraction

Supercritical CO_2 ($ScCO_2$) process has been recently applied method to recycle spent LIBs. This green technology enables us to recover precious parts from spent LIBs (Vauloup et al., 2026). It has unique properties including relatively low critical point (T_c = 31.1 °C, P_c = 7.38 MPa), good diffusivity, low viscosity and suitable for wide variety of applications (Bertuol et al., 2016).

Due to $ScCO_2$ is a non-polar solvent, it is highly effective for solving non-polar and low-molecular-weight compounds. Hence, $ScCO_2$ is appropriate for recovering non-polar electrolyte without generating toxic compounds (Zachmann et al., 2025). Organic liquid electrolytes, water-system electrolytes, inorganic solid electrolytes and polymer-based electrolytes are four groups that are used in LIBs. Among them, organic liquid electrolyte have been widely preferred in conventional LIBs due its high ionic conductivity and good suitability with electrode (Yang et al., 2025).

Zachmann et al (2024) have worked on recycling electrolyte from spent LIBs through sub- and supercritical CO_2 methods. Various process parameters including pressure (60-120 bar), temperature (15-55 °C) and duration (1-50 min) were examined. The recovery of non-polar electrolyte solvents was found to be strongly dependent on pressure and temperature, as these parameters directly influence the density of CO_2. At 80 bars, the electrolyte extraction yield reached the maximum level of 66% while increase in pressure (120 bar) resulted in a decrease on extraction. The same trend was observed for temperature; enhancing temperature above 29 °C resulted in decrease on extraction yield (Zachmann et al., 2024).

Another study was performed by Zachmann and Ebin (2025) to extract electrolyte solvents from Li-ion battery black mass through supercritical CO_2. They examined two different pressures; 100 and 140 bar at 40 °C. Under 140 bar and 40 °C, ethylene carbonates, biphenyl and propylene carbonate was extracted with high extraction yield >95% whereas under 100 bar, lower extraction yield of ethylene carbonate (60%) and propylene carbonate (50%) was achieved. For both pressure dimethyl carbonate, ethyl methyl carbonate and diethyl carbonate was successfully extracted with high extraction yield of >99% (Zachmann & Ebin, 2025). It was reported that utilizing $ScCO_2$ or liquid CO_2 effect on recovery of organic solvent. For example, EC has high recovery efficiency in $ScCO_2$ while DMC and EMC obtained with high recovery rate in liquid $ScCO_2$ (Yang et al., 2025).

Lithium carbonate ($LiCO_3$) and lithium hydroxide (LiOH) with high purity are ideal materials for cathode fabrication. In order to prevent Na_2CO_3 consumption to recover Li, Ramirez Velazquez et al (2024) examined the Li_2CO_3 production through chemical precipitation with CO_2 usage. Synthetic lixiviate was carbonated through varying process conditions including temperature (25, 50, 70 °C), stirring speed (300, 500 and 700 rpm) and reaction time (30 and 60 min). Results showed that reaction time was not enormous effect on final product's particle size. Stirring speed impacted on changing structures and crystal formation that increase in stirring speed resulted in creation of flower-like structures. With enhancement in temperature resulted in Li_2CO_3 yield and purity. Lithium carbonate that obtained at 25 °C showed amorphous morphology while products obtained at 50 °C and 70 °C formed flower-like structure. 99.9% of purity was achieved with re-precipitation step by CO_2 (Ramírez Velázquez et al., 2024).

Even though electrolyte recovery is possible with $ScCO_2$ without adding any chemical, metal recovery requires acid/organic acid addition, reducing agents such as H_2O_2.

Considering li-ion battery' market, $LiCoO_2$ is extensively utilized as cathode material for LIBs. It has high cobalt ration that is 60.2% of the mass of $LiCoO_2$, 32.7% of oxygen, and only 7.1% of lithium content. This high mass ratio of cobalt and commonly utilization of $LiCoO_2$ on market, makes cobalt ads the main element that needs to be recovered. Ibarra et al (2025) employed supercritical fluids technology to recover cobalt materials from spent $LiCoO_2$. Supercritical CO_2, super and subcritical water with using acid was performed to recover Co. Results showed that combination of citric acid and supercritical CO_2 method resulted in 99.49% of Co recovery whereas sub- and supercritical methods yielded in 60-70 % recovery efficiency. Compared to traditional chemical process, this technology offers lower energy consumption and reduced environmental impact (Morales Ibarra et al., 2025).

Unlike pure cathode active material, black mass has various impurities including graphite, residual carbon, metallic ingredients such as Al and Cu that formed from current collectors. Mahmoudi et al (2025) employed $ScCO_2$ to extract Li, Ni, Co and Mn from NMC black mass. They utilized $scCO_2$ as the solvent, ributyl phosphate–nitric acid (TBP-HNO_3) adducts as the chelating agent, tributyl phosphate–nitric acid (TBP-HNO_3) as the chelating agent and H_2O_2 as a reducing agent. More than 90% of extraction efficiency for Ni, Co, Mn was obtained under the conditions of 20.7 MPa pressure, at 65 °C, 5ml/g of adduct-to-solid ratio and 8 ml of H_2O_2 utilization. On the other hand, recovery of Li was around 73%. This was explained as ionic radius of Li is small so that it generates weak complex with TBP (Mahmoudi et al., 2025).

Zhang and Azimi (2022) investigated recovering four valuable critical metals from NMC by applying $ScCO_2$ solvent with tributyl phosphate–nitric acid and hydrogen peroxide adduct. They employed full factorial design to examine how temperature, pressure and adduct to solid ration impact on extraction. Results revealed that only adduct to sample is statically important and it impacts extraction efficiency. Increasing the adduct to solid ratio resulted in enhancement in metal extraction owing to providing more HNO_3 to react with the cathode material. Under the optimum conditions of 40 °C, 31 MPa, 1h, 5 ml/g adduct to solid ration and 759 rpm, 87% of Li, 90% of Co, 90% of Mn, and 89% of Ni extraction was achieved. Addition of 4% v/v H_2O_2 addition enhanced the extraction efficiency by 15-20% thanks to reducing metals to soluble forms (J. Zhang & Azimi, 2022).

Another study was performed by Bertual et al (2016) to recover Co from $LiCoO_2$ cathode active material though supercritical CO_2 with sulfuric acid and H_2O_2 as reducing agent.

They compared atmospheric pressure leaching and supercritical extraction in their study. Results showed that extraction time was reduced from 60 min to 5 min with employing $ScCO_2$ extraction instead of atmospheric pressure extraction. Moreover, H_2O_2 addition was reduced from 8% (v/v) to 4% (v/v) compared to atmospheric pressure extraction. The maximum extraction was achieved as 95.5% for Co within 5 min (Bertuol et al., 2016).

Advantages and Challenges of Green Recycling Technologies

Environmental concern of LIBs includes mining process of valuable raw materials, all production process and at the end of its life cycle. Habitats lose; water pollution and high carbon emissions are results of mining activities of these raw materials [80]. It is reported that 4000 t of spent LIBs produce nearly 1100 t of heavy metals and 200 t of toxic electrolytes. Based on cathode materials of LIBs, greenhouse gas emission (GHG) shows difference. For example, manufacturing of a 28-kWh battery of LFP, NMC, and LMO cathode materials emit 3061 $kgCO_2$-eq, 2912 $kgCO_2$-eq, and 2705 $kgCO_2$-eq GHG emissions, respectively [81].

Green recycling processes provide more environmentally friendly recovery of valuable materials compared to conventional processes. These processes have some advantages such as high recovery efficiency, being biodegradable, minimizing excess chemical usage, though they are also some challenges that need to be addressed to find large-scale applications in industry. In Table 1, the advantages and challenges of green recycling technologies are shown.

Table 1. The advantages and challenges of green recycling technologies

Technology	**Advantages**	**Challenges**
Bioleachin g	• It is considered as eco-friendly, safe-	• It is slower than chemical

	to handle, low-energy and low-cost method that generates fewer hazardous by-products than conventional pathways (Lalropuia et al., 2024; Moazzam et al., 2021; Roy et al., 2021). • Lab and pilot studies report very high leaching efficiencies for critical metals; up to ~90–100% Li, Co, Ni, Mn in various systems and cathode chemistries (Do et al., 2022; Xin et al., 2016). • Bioleaching can operate in one-step, two-step, and spent-medium (indirect) modes, decoupling microbial growth from leaching when needed (Biswal & Balasubramanian,	leaching, with kinetics governed by acidolysis, redoxolysis and complexolysis (Biswal & Balasubramanian, 2023; Roy et al., 2021). • Microbial activity is inhibited by high metal and pulp densities, requiring adaptation or low solids loading; processes are sensitive to pH, Fe^{2+}/S supply, and substrate concentration (Biswal & Balasubramanian, 2023; Lalropuia et al., 2024; Xin et al., 2016). • The LIB bioleaching is still on development stage hence it

	2023; Jiang et al., 2023). • It is possible to combined with electrokinetics or precipitation to recover metals as oxalates, hydroxides, or via electrowinning, forming closed-loop flowsheets (Do et al., 2022; Pakostova et al., 2024). • It enables much lower CO_2 emissions vs HCI leaching (16–19 vs 43–91 kg CO_2-eq per kg Co) (Alipanah et al., 2023).	is not commercialized yet (Biswal & Balasubramanian, 2023; J. Li et al., 2023).
Organic acid leaching	• High leaching efficiency (>90-99%) of Li, Co, Ni, Mn under optimized conditions (de Oliveira Demarco et al., 2019; Musariri et al., 2019; K. Wang, Zhang, & Luo, 2022).	• Due to their weak nature, it requires higher concentration, longer times or added oxidants such as H_2O_2, ascorbic acid to reach complete leaching (de Oliveira Demarco et al.,

	• Organic acids are biodegradable, less corrosive, and they prevent generation toxic gas emissions (Gerold et al., 2022; Jumari et al., 2022). • Lower leaching temperatures are often sufficient, cutting energy use and greenhouse gas (GHG) emissions (Gerold et al., 2022). • Numerous organic acids function as both acid and complexing/reducing agents, occasionally removing distinct reductants or facilitating synergistic leaching with mixed acids or H_2O_2 (Fatima et al., 2024; Xiao et al., 2021).	2019; Gerold et al., 2022; Xiao et al., 2021). • Particularly at high oxalate ratios when Li and Al co-extract, metal-organic compounds and co-precipitation (e.g., with oxalate) might make separation more difficult or lower precipitate quality (Schmitz et al., 2024; K. Wang, Zhang, Luo, et al., 2022). • Economics aims for low temperatures and high solid-liquid ratios, but sustaining good recovery in these circumstances is difficult and still requires

		optimization (Gerold et al., 2022; Roshanfar et al., 2024).
Deep Eutectic Solvents (DESs)	• It is green, tunable, and relatively safe. Compared to ILs, it can be synthesized easily and cheaply (Padwal et al., 2022; Svärd et al., 2024; Wen et al., 2024). • Many studies reported high leaching (95-100%) of Li, Co, Ni and Mn from LCO and NCM cathodes (Morina et al., 2022; Tran et al., 2019). • Some DESs provide stage-selective recovery. For example; Li-first, Co/Ni precipitation and separation (Cao et al., 2023; J. Wang et al., 2026). • DESs enables to be regenerated	• Based on used DESs, their viscosity can be high, and this is not enable mass transfer and handling (Goudarzi et al., 2025; B. Li et al., 2022). • Even though final leaching efficiency can be similar with inorganic acids, its reaction kinetics are 2-3 orders of magnitude slow (B. Li et al., 2022). • In contrast to great lab results, its progress cannot compete with mineral-acid hydrometallurgy at industrial

	and reused. Hence, it reduces waste generation and cost (B. Li et al., 2022; Y. Zhang et al., 2024b). • DESs can play multiple roles not only leaching but also removing binder, separation of cathode-collector, and direct regeneration (Gao et al., 2024; J. Wang et al., 2026).	scale, currently (Svärd et al., 2024; J. Wang et al., 2026). • It has operational complexity due to multiple precipitation steps, added reducing agents and control of pH/ligand (Y. Zhang et al., 2024b, 2024a; Zhou et al., 2025).
Ionic liquids	• It has low vapor pressure, low flammability, and tunable solubility. It provide decrease solvent losses and air emission than VOC (Meshram et al., 2025; Mušović et al., 2025). • Compared to conventional solvent extraction, it offers operating at lower	• Due to its relatively high viscosity, ion transport and reactions can be slow (Meshram et al., 2025; Mušović et al., 2025) • Many studies test only a few reuse cycles, and long-term stability, purity of recovered metals, and continuous

	temperature, enhanced selectivity and reduced emissions. Hence, it has lower energy and environmental footprint (Kovačević et al., 2024; Mušović et al., 2025)	operation remain under-explored (Mušović et al., 2025). • IL-based and direct recycling routes are still emerging, with challenges in efficient separation, binder removal, and process scale-up. Hence, it requires more studies to mitigate these challenges (Xu et al., 2023). • It is expensive so without meeting reusability of it, it can limit industrial adoption (Meshram et al., 2025; Xu et al., 2023)
Supercritical CO_2	• It offers high recovery (>90%) of Li, Co, Ni, and Mn from LIBs	• It is a weak solvent for highly polar salts such as

	and black mass, shorter reaction times and decreased H_2O_2 consumption than atmospheric leaching (Bertuol et al., 2016; Purnama et al., 2024; J. Zhang & Azimi, 2022) • It has highly efficient electrolyte recovery especially in organic carbonate solvents (> 95-99%) and binder removal (Zachmann et al., 2024; Zachmann & Ebin, 2025) • Changing process parameters such as temperature, pressure and co-solvents, it offers selectivity and tunability for non-polar organics, binders or metals (Han et al., 2023; Zachmann et al., 2024)	$LiFP_6$ and some cyclic carbonates, so it requires adding solvents to meet high recovery (Grützke et al., 2015; Zachmann et al., 2024) • It requires detailed investigation and industrial-scale validation for whole-process recycling (Cattaneo et al., 2024; Fu et al., 2021) • Even though $ScCO_2$ needs ≥74 var; many studies mostly apply 80-160 bar, so this needs expensive safety measures and pressure vessels (Fu et al., 2024;

		Zachmann et al., 2025)

Overall, green recycling technologies offer significant environmental advantages and high metal recovery efficiencies; however, challenges related to reaction kinetics, process optimization, scalability, and economic feasibility must still be addressed before their widespread industrial implementation.

Conclusion and Future prospects

Overall, green recycling technologies have emerged as promising alternatives to conventional pyrometallurgical and hydrometallurgical processes due to their lower environmental footprint, reduced energy consumption, and potential for selective recovery of critical metals from spent LIBs. Bioleaching, organic acid leaching, deep eutectic solvents (DESs), ionic liquids (ILs), and supercritical CO_2-based processes have all demonstrated high recovery efficiencies for valuable metals such as Li, Co, Ni, and Mn under optimized conditions. Furthermore, several of these approaches offer additional benefits, including reduced greenhouse gas emissions, solvent recyclability, lower toxicity, and the possibility of integrating multiple recycling steps within a single process. Despite these advantages, significant challenges remain before these technologies can achieve widespread industrial adoption. Common limitations include slow reaction kinetics, sensitivity to operating conditions, high solvent viscosity, complex downstream separation steps, and difficulties in maintaining high recovery efficiencies under economically favorable conditions such as high solid-to-liquid ratios. Moreover, many studies remain confined to laboratory-scale investigations, while long-term solvent stability, process integration, techno-economic feasibility, and large-scale validation are still insufficiently explored. Therefore, future research should focus on process intensification, solvent regeneration strategies, scale-up studies, and comprehensive life-cycle and techno-economic assessments to bridge the gap between laboratory performance and industrial implementation. Addressing these challenges will be essential for establishing commercially viable and environmentally sustainable LIB recycling systems capable of supporting the growing demand for critical battery materials within a circular economy framework.

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