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Research article

Carbon Nanoparticles Generated from Natural Sugars: Green Synthesis Approaches, Adsorption Mechanisms for Phenolic Compounds, and Potential Roles in Nanomedicine for Pancreatic Cancer

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Abstract: Carbon nanoparticles (CNPs) derived from natural sugars have gained significant attention as sustainable nanomaterials due to their low-cost precursors, simple synthesis, and environmentally friendly fabrication routes. Recent advances in green synthesis approaches—such as hydrothermal carbonization, microwave-assisted processes, and pyrolytic conversion—have enabled the production of highly tunable CNPs with controlled size, morphology, and surface functionalities. These structural features play a critical role in determining the adsorption behavior of CNPs toward phenolic compounds, offering promising applications in environmental remediation and water purification. Moreover, the inherent biocompatibility, photostability, and surface modifiability of sugar-derived CNPs have introduced new opportunities in nanomedicine, particularly in drug delivery systems for pancreatic cancer therapy. Functionalized CNPs exhibit enhanced cellular uptake, controlled drug release, and the ability to selectively target pancreatic cancer cells through active and passive targeting mechanisms. This review provides a comprehensive overview of green synthesis routes, physicochemical properties, adsorption mechanisms of phenolic contaminants, and emerging biomedical applications of sugar-based CNPs, with a special emphasis on their potential as innovative nanocarriers in pancreatic cancer treatment.

Keywords: Carbon nanoparticles; green synthesis; phenolic compounds adsorption; drug delivery; pancreatic cancer

1. Introduction

Carbon-based nanomaterials have emerged as one of the most versatile and widely explored classes of nanostructures due to their unique physicochemical properties, broad applicability, and relative ease of synthesis [1]. Among these materials, carbon nanoparticles (CNPs) synthesized from renewable, sugar-based precursors represent a rapidly growing area of interest driven by global trends toward sustainability, green chemistry, and environmentally benign nanomaterial production [2]. Natural sugars—such as glucose, sucrose, and fructose—are abundant, biocompatible, and structurally simple, making them ideal candidates for producing high-quality CNPs through eco-friendly routes [3].

Green synthesis approaches, including hydrothermal carbonization, microwave-assisted processes, and low-temperature pyrolysis, enable the fabrication of CNPs without the need for toxic solvents, harsh oxidizing agents, or energy-intensive methods, as shown in Figure (1) [4]. These techniques produce nanoparticles with tunable sizes, surface functionalities, and optical features, all of which can be precisely tailored for specific environmental or biomedical applications [5]. Notably, the oxygen-rich surface groups generated during green synthesis enhance the adsorption capacities of CNPs, particularly toward phenolic compounds, which are considered priority pollutants due to their toxicity, persistence, and widespread industrial use [6].

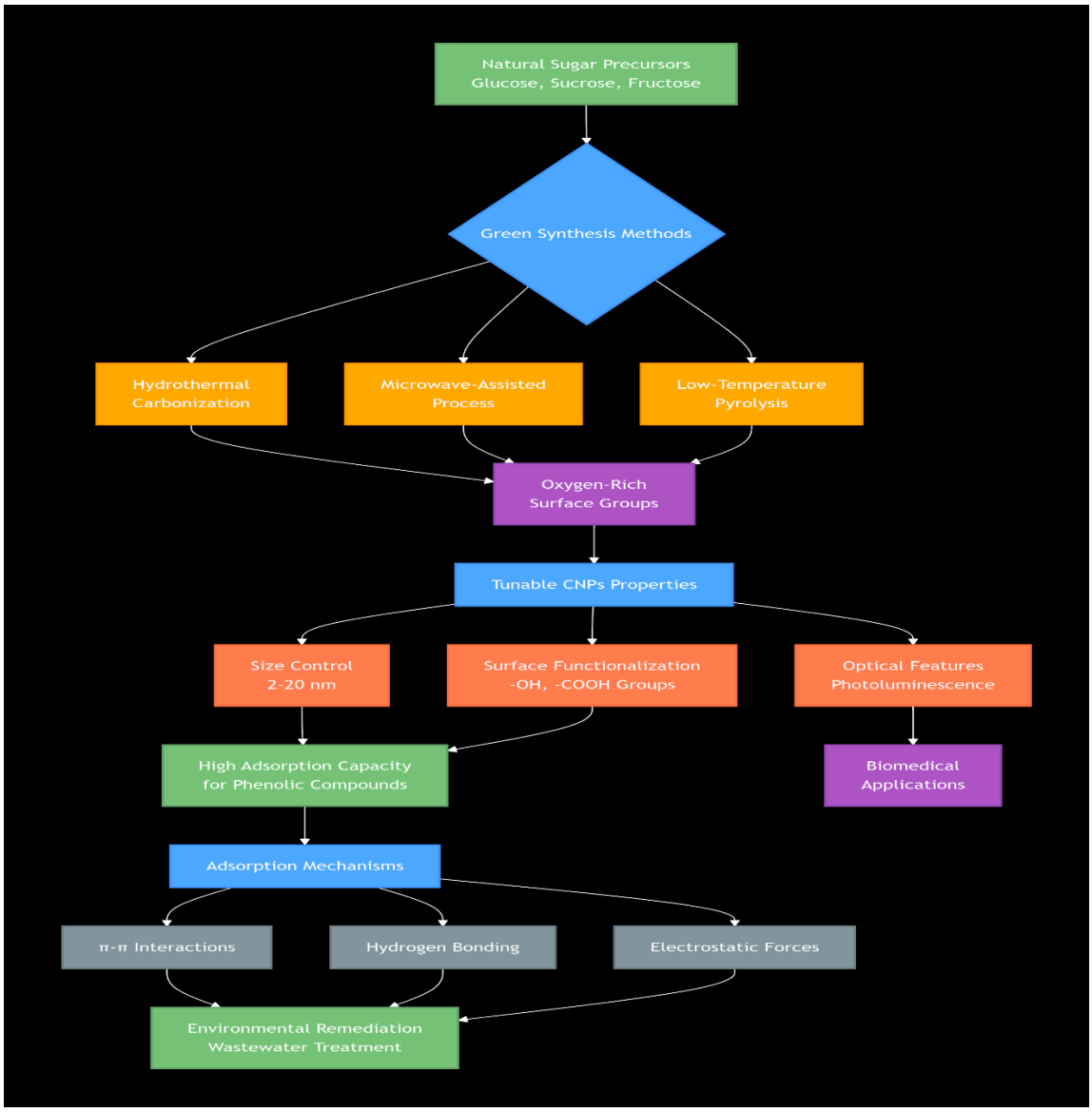


Figure 1. Shows the diagram of Green synthesis methods.

Beyond their environmental relevance, sugar-derived CNPs have demonstrated remarkable potential in nanomedicine, where their small size, aqueous dispersibility, low cytotoxicity, and ease of surface modification make them attractive candidates for targeted drug delivery systems [7]. Recent studies have highlighted their ability to deliver anticancer agents efficiently, enhance cellular uptake, and enable controlled release. This is especially significant for pancreatic cancer, one of the most aggressive malignancies with a poor prognosis and limited therapeutic options [8]. Developing advanced nanocarrier systems that improve drug selectivity and reduce systemic toxicity is a critical need in modern oncology [9]. In light of these advancements, this review provides a comprehensive overview of the state of the art in sugar-derived carbon

nanoparticles, focusing on their green synthesis strategies, structural and functional properties, mechanisms of phenolic pollutant adsorption, and emerging roles in nanomedicine. This review places special emphasis on their potential as novel drug-delivery platforms for pancreatic cancer, bridging environmental and biomedical perspectives within a single, unified framework.

2. Green Synthesis of Carbon Nanoparticles from Natural Sugars

The green synthesis of carbon nanoparticles (CNPs) from renewable sugar precursors has gained significant momentum as researchers seek sustainable alternatives to conventional carbon nanomaterial fabrication. Natural sugars—including glucose, fructose, sucrose, and polysaccharides—serve as excellent carbon sources due to their high carbon content, thermal responsiveness, and ability to undergo hydrothermal dehydration and aromatization [3]. Early studies demonstrated that hydrothermal carbonization (HTC) at moderate temperatures (160–220 °C) efficiently converts sugars into uniformly dispersed, spherical CNPs with rich oxygen-containing surface groups [10]. Later advancements introduced microwave-assisted synthesis, enabling rapid heating, reduced reaction times, and enhanced control over particle size and morphological uniformity [11]. Figure 2 shows the synthesis setup. Additional eco-friendly approaches, such as low-temperature pyrolysis, ultrasonic synthesis, and plant-extract–mediated methods, have further broadened the scope of green CNP production [12]. Also, Table 1 illustrates the Comparison of Green Synthesis Methods.

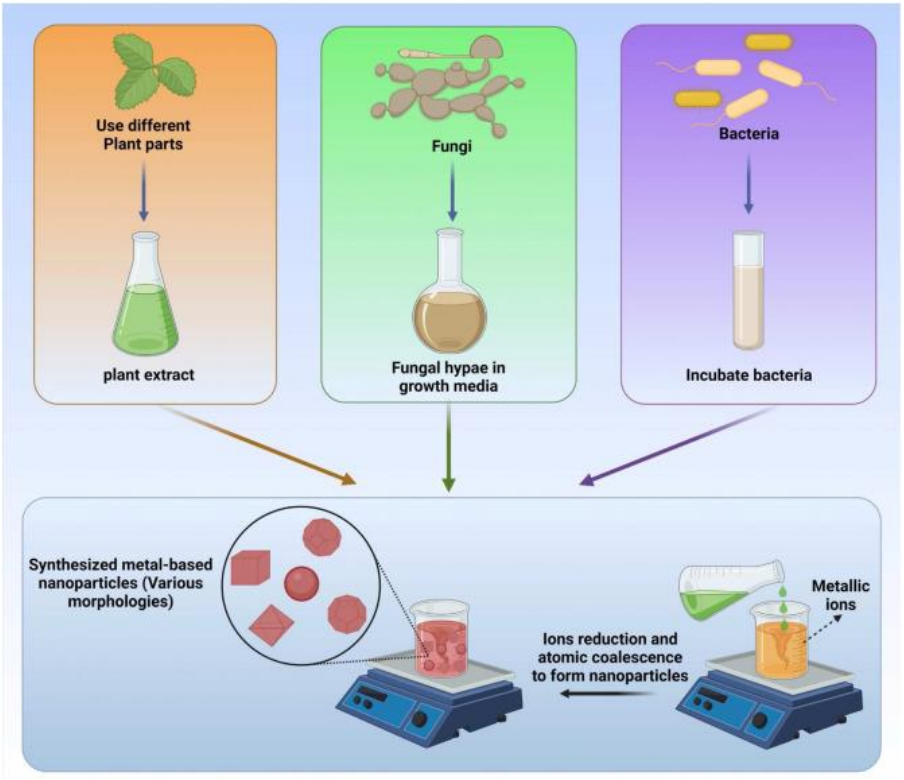


Figure 2. explains the setup of the synthesis Green Synthesis of Carbon Nanoparticles from Natural Sugars.

Table 1. Comparison of Green Synthesis Methods

Method	Carbon Source	Temp (°C)	Time	Particle Size (nm)	Notes
HTC	Glucose	180–220	4–12 h	5–20	Eco-friendly
Microwave	Sugars	120–200	5–30 min	2–10	Fast
Pyrolysis	Fructose	300–600	1–4 h	10–50	High energy
Ultrasound	Biomass	80–180	30–120 min	5–30	Moderate yield

A key advantage highlighted in the literature is the inherent tunability of sugar-derived CNPs. Reaction conditions—including temperature, pH, precursor concentration, and time—directly influence particle diameter, surface defects, optical absorption, and functional group distribution [5]. These structural features ultimately dictate CNP performance in environmental and biomedical applications. Studies consistently report that sugar-derived CNPs possess high aqueous dispersibility, photostability, and abundant hydroxyl, carboxyl, and carbonyl groups, making them particularly suitable for adsorption and biological interactions [13].

3. Structural Properties and Surface Chemistry of Sugar-Derived CNPs

Understanding the structural and chemical characteristics of CNPs is essential for evaluating their adsorption and biomedical potential. Numerous studies have shown that CNPs synthesized from sugars typically exhibit amorphous or partially graphitized carbon cores surrounded by functionalized shells rich in oxygen- and nitrogen-bearing groups, as shown in Figure 3 [14]. Advanced characterization methods—such as TEM, FTIR, XPS, and Raman spectroscopy—have revealed that these groups enhance both electron-transfer processes and molecular binding interactions. Table 2 presents the Physicochemical Properties of CNPs [15].

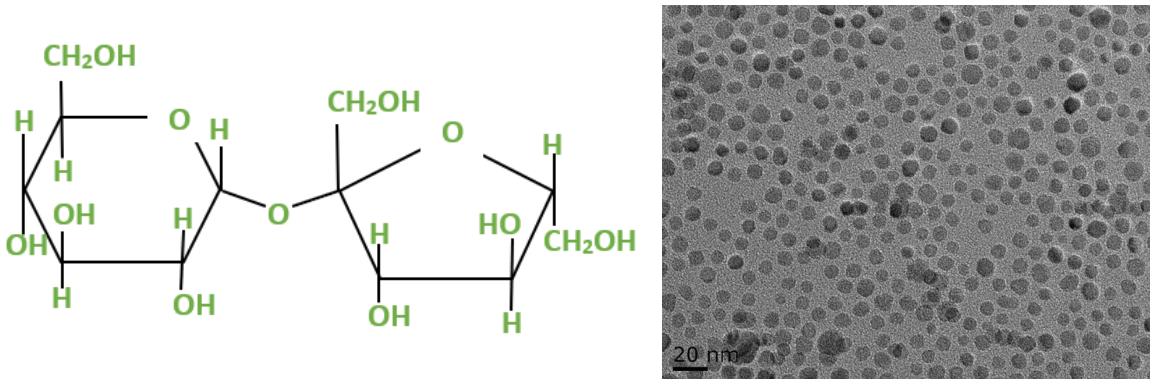


Figure 3. a)The Structure of Sugar-Derived CNPs, b) A TEM image

Table 2. Physicochemical Properties of CNPs

Property	Value
Size	2–20 nm
Zeta potential	-5 to -35 mV
Functional groups	OH, COOH, C=O
Fluorescence	Excitation-dependent
Biocompatibility	High

Size distributions ranging from 2 to 20 nm are commonly reported for CNPs synthesized under optimized conditions [16]. Optical studies indicate strong excitation-dependent fluorescence, making sugar-derived CNPs promising candidates for diagnostic and imaging applications [17]. The literature emphasizes that functionalization—either intrinsic (from synthesis) or engineered through post-treatment—plays a central role in modulating biocompatibility, adsorption capacity, and drug-loading efficiency [18].

4. Adsorption Mechanisms of Phenolic Compounds onto Carbon Nanoparticles

Phenolic pollutants, recognized as hazardous environmental contaminants, have motivated extensive research into adsorption-based removal strategies. CNPs derived from sugars have demonstrated considerable adsorption capacity toward phenolic compounds due to their high surface-to-volume ratio and functionalized surfaces [6]. Tables 3 and 4 will illustrate adsorption capacities and comparisons with carbon materials. Several studies have identified the dominant adsorption mechanisms, including:

- π–π interactions between the aromatic phenyl rings and graphitic domains of CNPs [19]
- Hydrogen bonding facilitated by hydroxyl and carboxyl groups on the nanoparticle surface [20]
- Electrostatic interactions depending on solution pH and surface charge [21]
- Van der Waals forces contributing to overall adsorption stability [22] will be shown in Figure (4) .

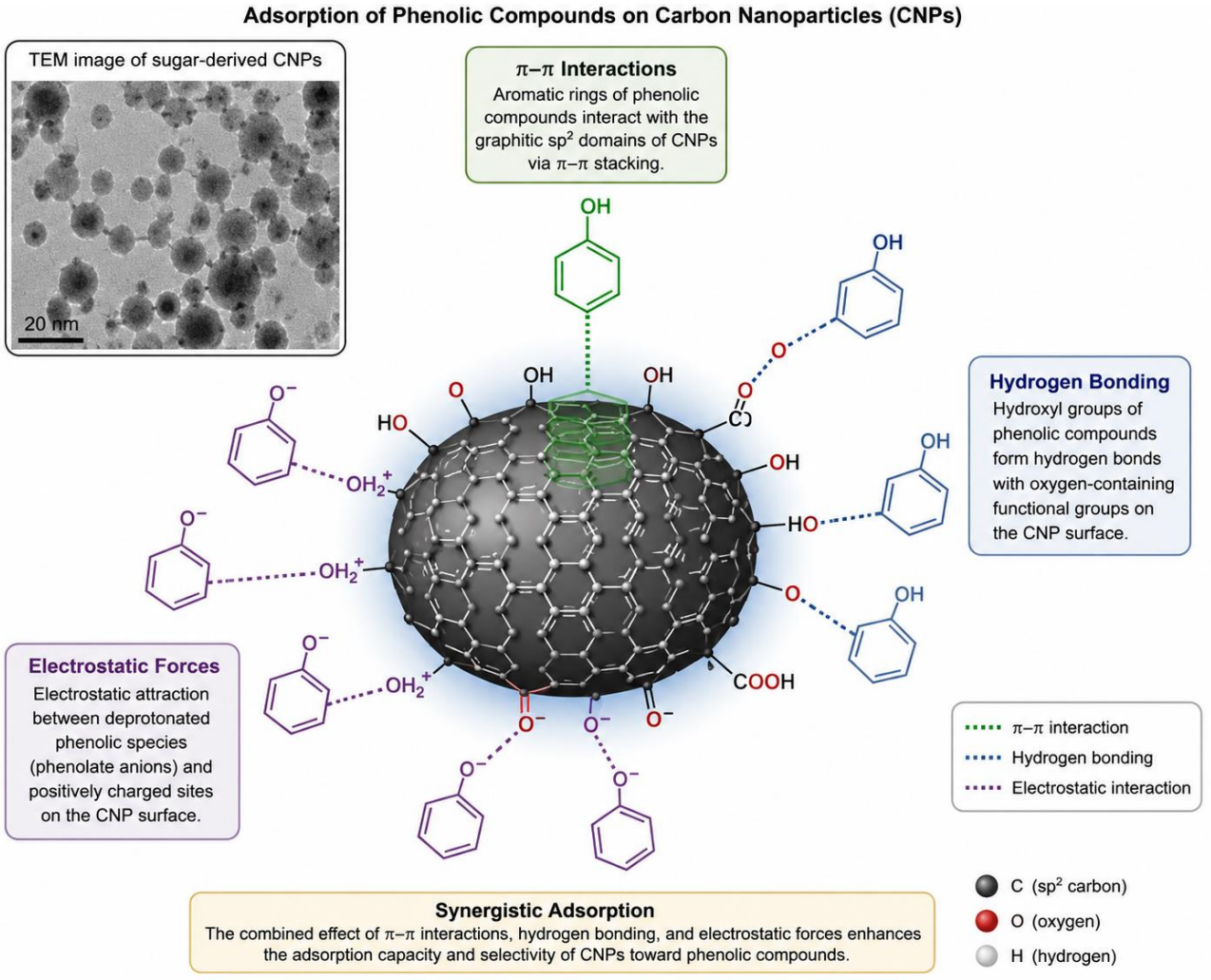


Figure 4. Adsorption Mechanisms of Phenolic Compounds onto Carbon Nanoparticles

Table 3. Adsorption Capacities

Adsorbent	Pollutant	Capacity (mg/g)	Mechanism
CNPs	Phenol	95–140	π–π, H-bond
CNPs	BPA	120–185	Hydrophobic
Activated Carbon	Phenol	280–550	Pore filling
Graphene Oxide	Phenol	110–200	π–π

Table 4. Comparison with Carbon Materials

Property	Sugar CNPs	Carbon Dots	GQDs	Activated Carbon
Biocompatibility	High	High	Medium	Low
Fluorescence	Moderate	High	High	None
Drug delivery	Good	Excellent	Excellent	Poor
Adsorption	Good	Moderate	Moderate	Excellent

The literature indicates that adsorption efficiency increases with decreasing particle size, higher surface oxygen content, and optimized pH [23]. Kinetic modeling frequently aligns with pseudo-second-order behavior, while isotherm analyses commonly fit the Langmuir model, suggesting monolayer adsorption on

homogeneous active sites [24]. These findings establish sugar-based CNPs as a viable and sustainable alternative to activated carbon and other traditional adsorbents [25].

5. Biomedical Applications and Biocompatibility of Carbon Nanoparticles

In recent years, sugar-derived CNPs have attracted notable interest in the biomedical sector because of their low toxicity, stable photoluminescence, and surface-engineering flexibility [7], as shown in Figure 5. Multiple *in vitro* and *in vivo* studies report excellent cytocompatibility across a range of cell lines, attributed to the absence of heavy metals and toxic byproducts typically associated with other nanomaterials [26]. Functionalization with biopolymers, targeting ligands, or therapeutic molecules further enhances cellular uptake and selective delivery capabilities [27].

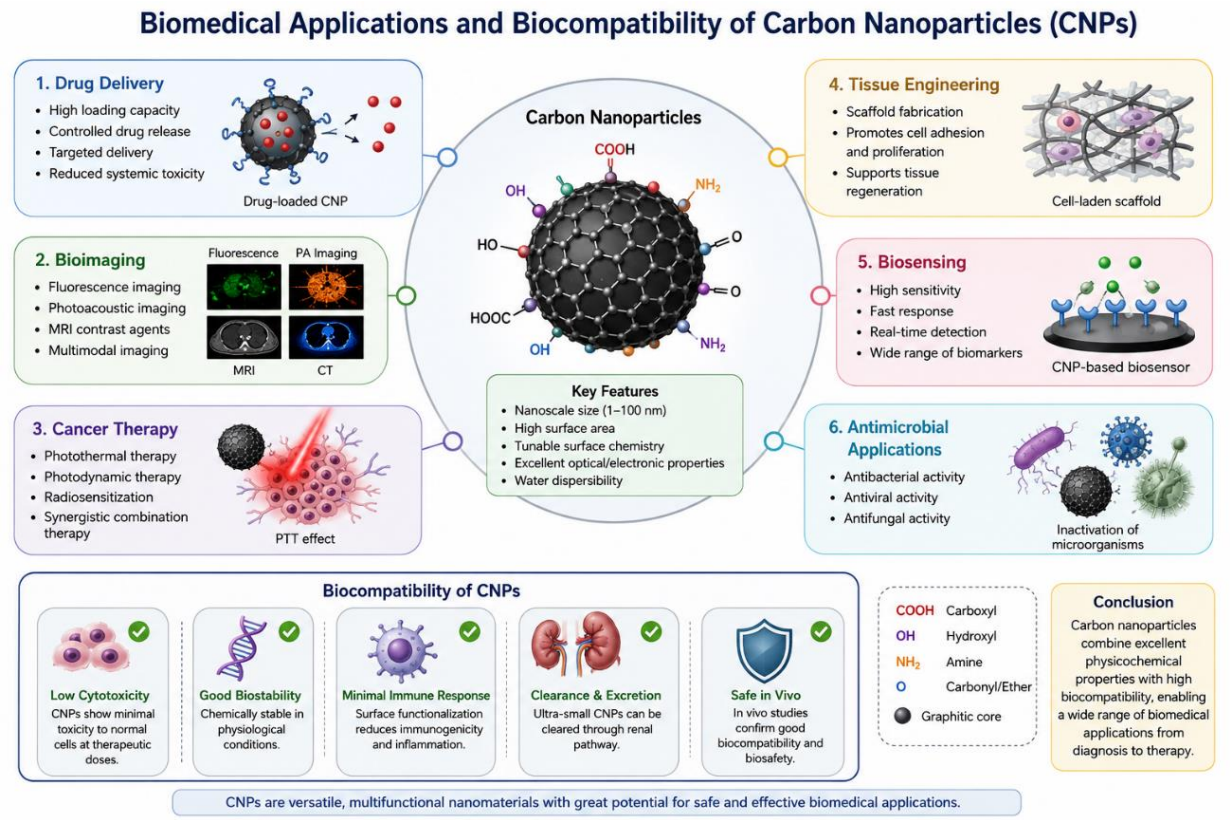


Figure 5. Biomedical Applications of Carbon Nanoparticles

Literature demonstrates the potential of CNPs in imaging, biosensing, gene delivery, antioxidant therapy, and antimicrobial applications [28]. However, drug delivery remains the most investigated direction because the particles can encapsulate or conjugate chemotherapeutic agents, respond to pH changes, and release drugs in a controlled manner [29]. Their small size allows for passive tumor targeting via the enhanced permeability and retention (EPR) effect, while surface modification facilitates active targeting through receptor–ligand interactions [30].

6. Potential of CNP-Based Nanocarriers in Pancreatic Cancer Treatment

Pancreatic cancer poses a significant therapeutic challenge due to late diagnosis, dense stromal architecture, and poor response to conventional chemotherapies [8]. Recent studies highlight carbon nanoparticles as promising nanocarriers that can enhance drug delivery efficiency and minimize systemic toxicity [31]. Sugar-based CNPs, in particular, offer biocompatible platforms for loading chemotherapeutics such as gemcitabine, doxorubicin, and paclitaxel, as shown in Table 5 [32].

Table 5. Drug Delivery in Pancreatic Cancer

Drug	Carrier	Loading %	Release	Outcome
Gemcitabine	CNPs	65–85%	Sustained	Enhanced cytotoxicity
Doxorubicin	CNPs	70–90%	pH-responsive	Improved uptake
Paclitaxel	CNPs	60–80%	Controlled	Tumor reduction

The literature shows that engineered CNPs can improve tumor penetration, enhance drug stability, prolong circulation time, and reduce off-target side effects [33]. Emerging research also explores integrating CNPs with targeting moieties such as folic acid, peptides, and antibodies specific to overexpressed pancreatic cancer receptors [34]. Furthermore, the intrinsic fluorescence of CNPs enables simultaneous imaging and therapeutic monitoring, paving the way for future theranostic applications [35]. Despite the significant progress achieved in the green synthesis and application of sugar-derived carbon nanoparticles (CNPs), a critical evaluation of the current literature reveals several important considerations regarding their practical performance and scalability. Various green synthesis techniques, including hydrothermal carbonization, microwave-assisted synthesis, and low-temperature pyrolysis, have been successfully employed to produce CNPs with tunable physicochemical properties. Hydrothermal carbonization is widely recognized for its simplicity, high product quality, and preservation of oxygen-containing functional groups; however, relatively long reaction times remain a limitation. In contrast, microwave-assisted synthesis offers rapid production and improved control over particle size distribution but may present challenges for large-scale industrial implementation. Pyrolysis methods often generate materials with higher degrees of carbonization and graphitic character, although they generally require higher energy input and may reduce surface functionality [36–39].

From an environmental perspective, sugar-derived CNPs have shown promising adsorption capacities for phenolic pollutants through multiple mechanisms, including π–π interactions, hydrogen bonding, electrostatic attraction, and van der Waals forces. Nevertheless, adsorption performance varies considerably depending on precursor type, synthesis conditions, particle size, and surface chemistry. While several studies have reported adsorption efficiencies comparable to or exceeding those of conventional activated carbon, direct comparisons remain difficult because experimental conditions, pollutant concentrations, and adsorption models vary. Therefore, standardized evaluation protocols are necessary to establish reliable performance benchmarks and facilitate comparison among different carbon-based adsorbents [40–42]. In biomedical applications, sugar-derived CNPs possess several advantages over many conventional nanocarriers, including low toxicity, excellent aqueous dispersibility, intrinsic fluorescence, and facile surface functionalization. Compared with activated carbon, they offer superior biocompatibility and drug-delivery potential, while costing less to produce than graphene quantum dots and several engineered carbon nanostructures. Furthermore, their abundant surface functional groups enable efficient loading of therapeutic agents and targeted delivery strategies. However, challenges related to drug-loading efficiency, long-term biodistribution, pharmacokinetics, and large-scale manufacturing remain insufficiently investigated [43–45]. Particularly in pancreatic cancer therapy, CNP-based nanocarriers have shown encouraging potential for enhancing the delivery of chemotherapeutic agents such as gemcitabine, doxorubicin, and paclitaxel. Their nanoscale dimensions facilitate tumor accumulation through the enhanced permeability and retention (EPR) effect, while targeted surface modifications may further improve cellular uptake and therapeutic selectivity. Nevertheless, most available studies remain limited to laboratory-scale investigations, with relatively few in vivo studies and no comprehensive clinical evaluations. Future research should focus on systematic comparisons between sugar-derived CNPs and other carbon nanomaterials, optimization of drug-loading and release profiles, assessment of long-term safety, and development of scalable green manufacturing processes to support potential clinical translation [46–49].

7. Discussion

The collective body of research on carbon nanoparticles (CNPs) synthesized from natural sugars highlights their significant promise across environmental and biomedical domains; however, key considerations remain regarding their performance, scalability, and clinical translation. The green synthesis routes discussed in the literature offer clear advantages in sustainability, simplicity, and environmental safety [4, 10]. Hydrothermal and microwave-assisted methods, in particular, consistently yield nanoparticles with controlled morphology and surface chemistry [11]. Yet a major limitation is the lack of standardized synthesis protocols, which makes it difficult to compare results across studies and to optimize nanoparticles for specific applications [50]. Differences in precursor types, reaction conditions, and purification procedures often lead to inconsistent physicochemical properties, suggesting a need for more systematic and reproducible fabrication frameworks [5]. From an environmental standpoint, sugar-derived CNPs exhibit strong adsorption capacities toward phenolic pollutants, primarily due to their oxygen-rich functional groups and tunable surface properties [6, 23]. Although several studies demonstrate high removal efficiency under laboratory conditions, challenges persist in translating these results to real wastewater systems. Factors such as competing ions, variable pH, and organic matter can significantly influence adsorption effectiveness [51]. Moreover, the regeneration and reusability of CNP-based adsorbents remain insufficiently explored [52]. Long-term stability and potential environmental impacts of nanoparticle release must also be thoroughly evaluated before scaling these materials for industrial remediation processes [53]. In the biomedical field, CNPs offer clear advantages due to their biocompatibility, photostability, and ease of functionalization [7, 18]. However, despite promising in vitro results, their in vivo performance—particularly in complex, treatment-resistant cancers such as pancreatic cancer—remains insufficiently validated [54]. The tumor microenvironment in pancreatic cancer is notoriously dense and hypovascular, presenting significant barriers to nanoparticle penetration [8]. While functionalized CNPs have shown improved cellular uptake and targeted delivery in preclinical models, more comprehensive pharmacokinetic and biodistribution studies are needed to evaluate their therapeutic potential and safety profiles [55].

Another major gap in the literature involves the long-term toxicity and biodegradation of sugar-derived CNPs. Although short-term cytotoxicity studies generally indicate high biocompatibility, the metabolic fate, clearance routes, and potential accumulation of these nanoparticles in organs require further investigation [56]. The lack of standardized toxicology frameworks hinders the advancement of these materials toward clinical applications [57]. A final consideration involves the dual-use nature of sugar-derived CNPs in environmental remediation and nanomedicine. While this versatility highlights their value, it also underscores the need to tailor nanoparticle properties to specific applications. Adsorption efficiency and drug delivery performance often rely on distinct surface chemistries, sizes, and functional groups [5, 18]. Thus, future research should focus on engineering application-specific CNP variants through controlled synthesis, post-modification, or hybridization with other nanomaterials [58]. The accumulated body of research on sugar-derived carbon nanoparticles (CNPs) highlights their considerable potential in both environmental and biomedical applications; however, their practical implementation is still limited by several key challenges. Green synthesis approaches, particularly hydrothermal and microwave-assisted methods, offer advantages in terms of simplicity, sustainability, and the ability to produce nanoparticles with tunable surface chemistry and morphology [58,59]. Nevertheless, the lack of standardized synthesis protocols leads to significant variations in physicochemical properties across studies, limiting reproducibility and meaningful comparison of results [59,60]. From an environmental perspective, these nanoparticles demonstrate strong adsorption efficiency toward organic pollutants such as phenolic compounds, mainly due to their oxygen-rich functional groups [61]. However, their performance in real wastewater systems is often reduced by competing ions, pH fluctuations, and organic matter, while studies on regeneration, reusability, and long-term stability remain insufficient [61,62]. In the biomedical field, CNPs exhibit good biocompatibility and strong potential for surface functionalization, yet their in vivo efficacy, particularly in complex malignancies such as pancreatic cancer, remains inadequately validated due to biological barriers that hinder tumor penetration [63,64]. Furthermore, critical gaps persist in understanding their pharmacokinetics, biodistribution, and long-term toxicity, limiting clinical translation [63,65]. Overall, advancing these materials toward real-world

environmental and medical applications requires standardized synthesis strategies, comprehensive in vivo studies, and a deeper mechanistic understanding of their structure–function relationships [59,64].

8. Conclusions

Carbon nanoparticles (CNPs) synthesized from natural sugars represent a promising class of eco-friendly nanomaterials with diverse applications in environmental remediation and nanomedicine. Green synthesis routes—such as hydrothermal carbonization, microwave-assisted processing, and low-temperature pyrolysis—demonstrate that high-quality CNPs can be produced sustainably, with tunable structural and surface properties [2, 4]. These features directly contribute to their notable adsorption efficiency toward phenolic pollutants, positioning sugar-derived CNPs as viable alternatives to conventional adsorbents in water treatment [6, 25]. At the same time, extensive research underscores their growing potential in biomedical applications, particularly in drug delivery systems designed for difficult-to-treat cancers such as pancreatic cancer [7, 31]. Their small size, biocompatibility, fluorescence, and ease of functionalization enable CNPs to act as effective nanocarriers that improve therapeutic selectivity and minimize systemic toxicity [5, 32]. Despite these advancements, several challenges remain, including the lack of standardized synthesis protocols, limited long-term toxicity assessments, and insufficient *in vivo* studies that evaluate their performance and safety in realistic biological environments [36, 42]. Additionally, environmental factors affecting adsorption efficiency and the needs of application-specific nanoparticle design require further investigation [37, 44]. Overall, sugar-derived CNPs present a versatile and sustainable nanoplatform with significant potential, but future research must focus on scaling up green synthesis, enhancing application-specific engineering, and establishing comprehensive toxicological frameworks. These efforts will be crucial to translating the laboratory promise of carbon nanoparticles into real-world environmental technologies and clinically relevant cancer nanotherapeutics.

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