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Biomass-Derived Nanocarbons for Antimicrobial Therapy: A Sustainable Pathway for Developing Health Infrastructure

Prof. Hezam Saleh Mohammed Dhaif Allah

Independent Researcher, Master of Pharmacy – Pharmaceutics, Department of Pharmaceutical Sciences
Nationality: Yemeni

Abstract

Nanocarbon-based drug delivery systems have gained increasing attention as advanced platforms for enhancing antimicrobial therapy, particularly in low-resource settings where drug resistance and limited healthcare infrastructure remain critical challenges. Among various nanocarbon materials, biomass-derived nanocarbon and carbon-based nanoparticles offer a unique combination of low-cost production, high surface area, tunable surface chemistry, and efficient drug loading capacity, making them especially suitable for developing countries.

This review provides a focused and critical analysis of recent advances in nanocarbon-based systems for antimicrobial drug delivery, with particular emphasis on their role in improving the efficacy of conventional antibiotics such as azithromycin. Key mechanisms including drug adsorption, controlled release, and targeted delivery are discussed in relation to their ability to overcome antimicrobial resistance and enhance therapeutic outcomes.

Furthermore, this study highlights the potential of sustainable and locally sourced nanocarbon materials as scalable solutions for decentralized pharmaceutical production. Critical challenges related to toxicity, regulatory limitations, and manufacturing reproducibility are also evaluated, with emphasis on their implications in low-resource healthcare systems.

Finally, a conceptual framework is proposed to bridge the gap between laboratory-scale innovation and clinical translation in developing countries. This work provides new insights into the integration of sustainable nanotechnology and antimicrobial therapy, offering a practical pathway toward affordable and effective drug delivery solutions in resource-limited environments.

Keywords: Nanocarbon; Drug Delivery Systems; Developing Countries; Sustainable Nanotechnology; Antimicrobial Resistance

Introduction

Nanocarbon materials including carbon nanotubes (CNTs), graphene, graphene oxide, and carbon quantum dots are a class of advanced nanostructured materials with unique physicochemical properties that make them highly suitable for biomedical applications, especially drug delivery. These carbon-based nanomaterials are characterized by high surface area, versatile surface chemistry, and the ability to be functionalized for specific targeting, which enable efficient loading and controlled release of therapeutic agents. Their remarkable attributes have positioned them as promising carriers capable of enhancing drug

stability, improving bioavailability, and reducing systemic toxicity when compared to conventional drug delivery systems. [1]

Carbon nanomaterials can encapsulate or adsorb various classes of drugs ranging from small molecules to proteins and nucleic acids while offering opportunities for stimuli-responsive release, targeted delivery, and multifunctional therapeutic platforms. [2]

The translation of nanocarbon-based drug delivery systems into clinical and healthcare applications holds particular relevance for developing countries, where the burden of infectious diseases, cancer, and chronic conditions remains substantial. Nanocarriers can address several healthcare challenges in resource-limited settings by improving therapeutic efficacy while reducing dosing frequency and treatment costs. The ability to functionalize carbon nanocarriers enables precise drug targeting, which can decrease adverse effects and improve patient compliance an important consideration where continuous clinical monitoring may be limited. [3]

Moreover, nanocarbon platforms show promise in enhancing the delivery of poorly soluble or labile drugs, extending their circulation times in vivo and potentially reducing the quantity and frequency of dosage required. Such enhancements can minimize treatment costs and logistical burdens on healthcare systems with limited infrastructure.[3]

Despite the significant advancements in carbon-based nanotechnology, comprehensive assessments that examine both the scientific potential and implementation challenges in the context of developing countries are limited. This review aims to synthesize current evidence from recent scientific literature (post-2020) on the rationale, opportunities, and translational pathways for nanocarbon-based drug delivery systems, with specific focus on their ability to improve drug stability and efficacy, reduce dosing frequency and side effects, and contribute to tackling global health challenges such as antimicrobial resistance. [2]

By critically evaluating the biological advantages, material design strategies, and potential socio-economic implications for healthcare systems in low-resource settings, this review provides a scientifically grounded framework to inform future research, policy considerations, and clinical translation efforts. [3]

Despite the tremendous potential of carbon-based nanocarriers in enhancing drug delivery, several significant challenges and limitations must be addressed—especially with respect to translation into real-world healthcare applications in developing countries.

One of the critical barriers is toxicity and biocompatibility concerns. Carbon nanomaterials such as carbon nanotubes (CNTs), graphene derivatives, and other allotropes may interact unpredictably with biological systems, leading to inflammatory responses, immune activation, or organ accumulation that could harm patients. Comprehensive toxicity assessments and long-term studies are therefore essential before clinical implementation. [4]

Another major challenge is scalability and manufacturing consistency. Ensuring uniform particle size, shape, surface chemistry, and drug-loading efficiency at large production scales is technically difficult and can be an economic barrier—particularly for low-resource settings where advanced fabrication facilities may be limited. [4]

In addition, regulatory and safety evaluation frameworks for nanomedicines, especially emerging carbon platforms, are not yet fully standardized. This regulatory ambiguity can delay approval processes, hinder clinical translation, and increase development costs—limiting access in developing countries. [5]

Biological and clinical barriers also exist, including uncertainties in nano–bio interactions, unpredictable biodistribution, and the lack of standardized testing protocols to evaluate nanomaterial behavior in

complex biological environments. These factors complicate the design of safe and effective nanocarrier systems that can be widely adopted. [6]

Overcoming these challenges will require interdisciplinary research, robust safety studies, scalable manufacturing technologies, and adaptive regulatory pathways tailored to emerging nano-therapeutics. Addressing these barriers is crucial to unlocking the full benefits of nanocarbon drug delivery for global health.[4]

Looking forward, the integration of advanced material engineering and artificial intelligence (AI) offers promising routes to overcome current limitations of carbon nanocarrier systems. For example, AI-guided design can optimize nanocarrier properties for enhanced targeting and reduced toxicity, potentially enabling safer and more effective formulations. [7]

Functionalization strategies—such as polymer coatings, peptide conjugation, or targeting ligands—are advancing the biocompatibility and specificity of carbon nanomaterials, which could improve clinical outcomes and reduce off-target effects in vulnerable populations. [8]

Furthermore, collaborative global research efforts that include stakeholders from academia, industry, and regulatory agencies are essential to accelerate translation. For developing countries specifically, building local expertise and technology transfer initiatives can facilitate adoption of affordable, scalable nano-based therapies tailored to local disease burdens.

Despite the challenges, the rapid pace of innovation in nanocarbon drug delivery—supported by multidisciplinary research and evolving technologies—suggests a strong potential to revolutionize therapeutics and reduce health disparities worldwide.

Overview of Nanocarbon Materials

1. Carbon Nanotubes (CNTs)

Carbon nanotubes are one-dimensional cylindrical nanostructures formed by rolling one or more layers of graphene into tubes. They can be single-walled (SWCNTs) or multi-walled (MWCNTs), each exhibiting exceptional mechanical strength, electrical and thermal conductivity, and high aspect ratio. These properties make CNTs attractive for a wide range of applications, including drug and gene delivery, biosensing, and nanocomposite reinforcement. Their hollow porous structure also enables high drug loading and controlled release when appropriately functionalized. [9]

2. Graphene and Graphene Oxide (GO)

Graphene is a two-dimensional (2D) single layer of sp^2-bonded carbon atoms arranged in a hexagonal honeycomb lattice. It exhibits extraordinary strength, conductivity, and surface area, making it a key building block for many carbon nanomaterials. Graphene can be chemically modified to form derivatives such as graphene oxide (GO)—which contains oxygen-functional groups that improve dispersibility and functionalization potential for drug loading and biocompatibility—and reduced graphene oxide (rGO), which balances conductivity with functional group availability. [10]

Graphene oxide, in particular, has garnered significant interest in drug delivery due to its biocompatibility, high drug loading capacity, controlled release potential, and multifunctional platform capabilities for targeting and imaging applications. [11]

3. Carbon Dots (CDs)

Carbon dots (CDs), also known as carbon quantum dots (CQDs), are zero-dimensional nanometer-sized carbon particles (<10 nm) that exhibit unique optical and electronic properties, including strong fluorescence, good water solubility, and surface-dependent biocompatibility. CDs can be synthesized

using top-down or bottom-up approaches and have applications in bioimaging, biosensing, and drug delivery due to their tunable surface chemistry and low toxicity. [12]

4. Activated Carbon

Activated carbon is a porous carbon material characterized by high surface area and tunable pore size distribution, typically produced by chemically or physically activating carbonaceous precursors (e.g., coal, wood, or biomass). In nanotechnology and biomedical fields, activated carbon and porous carbon structures serve as adsorbents, carriers, and support materials due to their affordability, scalability, and excellent adsorption properties for small molecules. Although activated carbon itself is not a defined "nanocarbon" in every case, nanostructured activated carbon materials are increasingly explored for controlled release and adsorptive drug delivery applications. [13]

5. Biochar-Derived Nanocarbon

Biochar is a carbonaceous solid material derived from biomass pyrolysis under limited oxygen conditions. When biochar is reduced into nanoscale structures (e.g., nanobiochar or biochar-derived carbon dots), it combines sustainability with unique surface properties. These biochar-derived nanocarbons exhibit strong adsorption capabilities, potential antimicrobial properties, and cost-effective synthesis routes, making them promising for environmental remediation, drug delivery platforms, and antimicrobial applications, especially when green and low-cost production is considered. [14]

Biochar-derived carbon dots can also be synthesized for biomedical sensing and therapeutic applications, representing a sustainable route to functional nanocarbon materials. [15]

Physicochemical Properties Relevant to Drug Delivery

Carbon-based nanomaterials possess several key physicochemical properties that make them highly suitable as drug delivery platforms. These properties influence how effectively drugs can be loaded onto carriers, released in controlled fashions, interact with biological environments, and ultimately improve therapeutic outcomes.

1. Surface Area and Porosity

One of the most important physicochemical characteristics of carbon nanomaterials is their large specific surface area and porosity, which directly influence drug loading capacity and kinetic release profiles. Nanostructured carbon carriers—like mesoporous carbon nanoparticles (MCNs)—feature extensive networks of pores and high surface area that facilitate the adsorption and encapsulation of drug molecules. These structural features not only enhance the loading capacity for a wide range of therapeutic agents but also allow modulation of release kinetics, including sustained and controlled release. MCNs' adjustable pore volume and surface chemistry make them versatile for immediate, sustained, and targeted drug delivery systems. [16]

2. Surface Functionalization

Surface functionalization refers to the deliberate modification of nanocarrier surfaces with chemical groups (e.g., carboxyl, hydroxyl, amine) or biomolecules (ligands, polymers) to enhance functionality. In carbon nanomaterials, surface modification improves dispersion in biological fluids, increases biocompatibility, and enables targeted delivery by recognizing specific tissues or cellular receptors. Functionalization also plays a critical role in tuning interactions between carriers and drug molecules, influencing binding affinities, stability, and release patterns. For instance, engineered surface groups help control nonspecific binding and can significantly reduce cytotoxicity while promoting enhanced uptake by target cells. [17]

3. Drug Loading and Release Mechanisms

The mechanism of drug loading onto carbon carriers depends on both physical and chemical interactions. High surface areas and pore volumes allow for adsorption, encapsulation, or π–π interactions with aromatic drug molecules, leading to high payload capacities. Following loading, controlled and stimuli-responsive release can be achieved via mechanisms such as:

Diffusion-controlled release, based on concentration gradients.

pH-responsive release, where drug release speeds increase in acidic environments (e.g., tumor tissues).

External stimuli triggers, such as light or redox conditions, which cause the carrier to release drug molecules at desired times.

These release strategies help maintain therapeutic drug concentrations over extended durations, reducing dosing frequency and minimizing side effects. [16]

4. Biocompatibility Considerations

For clinical translation, biocompatibility is a critical requirement of any drug delivery system. Carbon nanomaterials often exhibit favorable biological interactions when appropriately engineered. Their biocompatibility is linked to:

Controlled surface chemistry that reduces cytotoxicity and immunogenic responses.

Particle size and shape influencing cellular uptake without causing undue inflammation.

Functionalization with biocompatible polymers or targeting ligands to mitigate aggregation and off-target effects.

Although many carbon nanomaterials demonstrate good compatibility with biological systems, comprehensive in vivo toxicity studies remain essential to understand long-term safety profiles—especially for clinical applications in humans. [17]

Carbon-based nanocarriers such as mesoporous carbon, carbon dots, carbon nanotubes, and graphene derivatives—combine these physicochemical properties to improve the therapeutic potential of a variety of drugs across multiple disease models.

Nanocarbon-Based Drug Delivery Systems

Carbon-based nanomaterials (CNMs) such as carbon nanotubes (CNTs), graphene and its derivatives, carbon dots (CDs), and mesoporous carbon are being intensively studied as advanced drug delivery platforms due to their large surface areas, versatile surface chemistries, and capacity for functionalization and stimuli-responsive release. These properties allow CNMs to be tailored for efficient drug loading, specific targeting, and controlled therapeutic release, which can significantly improve treatment effectiveness while lowering systemic side effects. [18]

1. Drug Adsorption vs. Covalent Attachment

Drug loading onto carbon nanocarriers can occur primarily through two mechanisms:

Adsorption (Non-Covalent Interactions):

This involves physical interactions such as π–π stacking, hydrophobic interactions, van der Waals forces, and electrostatic adsorption between the drug and the nanocarrier surface.

Non-covalent adsorption preserves the chemical integrity of many drugs (especially sensitive biomolecules) and often enables stimuli-responsive or pH-dependent release—for example, drugs bound via π–π interactions can detach under acidic conditions at tumor sites.

Adsorption is widely used for drugs such as doxorubicin on carbon nanostructures like PEG-modified CNTs, enabling pH-responsive and controlled release. [18]

Covalent Attachment:

Involves chemical bonds (e.g., ester, amide linkages) between the drug and functional groups on the surface of the nanocarrier.

Covalent conjugation often enhances stability and circulation time by firmly anchoring the drug to the carrier and can reduce premature drug leakage before reaching the intended site.

However, covalent bonds may slow the release rate and require stimuli-cleavable linkers (pH-sensitive, enzyme-sensitive) to achieve controlled release in targeted environments. [18]

Both methods are critical design strategies in CNM-based systems, and the choice between adsorption and covalent attachment depends on the desired release profile, drug properties, and therapeutic context. [19]

2. Targeted vs. Non-Targeted Delivery

Non-Targeted (Passive) Delivery:

Non-targeted delivery systems rely on physicochemical behavior and circulation dynamics to accumulate at sites of interest (e.g., enhanced permeability and retention effect in tumors).

Many carbon nanocarriers naturally accumulate in tissues with leaky vasculature through EPR (enhanced permeability and retention) which increases local drug concentrations without specific targeting ligands.

Targeted (Active) Delivery:

Active targeting is achieved by functionalizing nanocarriers with ligands such as antibodies, peptides, aptamers, or small molecules that bind to specific receptors on target cells.

Carbon nanomaterials can be engineered with such targeting moieties on their surface to improve uptake by diseased cells while sparing healthy cells, thus reducing systemic toxicity and enhancing therapeutic efficacy.

For example, non-covalently functionalized carbon nanostructures with hyaluronic acid (targeting CD44 receptors) improve uptake in breast cancer cells, demonstrating how surface functionalization enables active targeting. [18]

Therefore, CNM drug delivery systems can be designed for either broad systemic distribution or precision targeting, depending on the clinical objective and ligand functionalization. [18]

3. Controlled and Sustained Release Profiles

An essential design goal of modern DDS is to achieve controlled and sustained drug release, allowing drugs to be delivered at a therapeutic concentration for extended periods while reducing dosing frequency and side effects. Carbon nanomaterials support this through various mechanisms:

Stimuli-Responsive Release:

CNMs can be engineered to release drugs in response to endogenous stimuli such as pH changes, redox conditions, enzymes, or exogenous triggers like temperature, light, or magnetic fields.

For example, carbon nanoonions functionalized for pH-responsive release exhibit significantly different drug release rates under acidic conditions (typical of tumor microenvironments), enabling site-specific activation of drug payloads. [18]

Sustained Release:

Certain nanocarriers allow a slow and continuous release of bound drugs over extended timeframes, improving pharmacokinetics and therapeutic outcomes.

Mesoporous carbon nanostructures, due to their pore architecture and high surface area, can sustain drug release over days, maintaining therapeutic levels while reducing the need for frequent dosing. [17]

Gatekeepers and Functional “Caps”:

Advanced strategies use surface modifiers or polymer "gatekeepers" that respond to physiological triggers, controlling the timing and rate of drug release, enhancing safety and efficacy. [20]
Overall, controlled and sustained release profiles are fundamental to maximizing the clinical benefit of CNM-based nanocarriers by ensuring predictable drug kinetics aligned with the therapeutic window.

herapeutic Applications

Carbon-based nanomaterials—including *carbon dots (CDs), carbon nanotubes (CNTs), graphene derivatives, and related nanostructures—have emerged as versatile platforms for delivering therapeutic agents in a range of medical applications. Their unique nano-scale properties (such as high surface area, tunable surface chemistry, and biocompatibility) enable enhanced targeted delivery, controlled release, and multifunctional therapeutic actions across diverse disease conditions. [21]

1. Antimicrobial Drug Delivery

Carbon dots (CDs) and other nanocarbon carriers have shown potent antimicrobial activity and enhanced drug delivery capabilities against bacteria and other pathogens. CDs can be engineered to improve drug solubility, cellular uptake, and site-specific release of antibacterial agents, resulting in increased therapeutic efficacy and reduced systemic toxicity compared to conventional formulations. Their high surface area and surface functional groups facilitate loading of antibiotics and antimicrobial drugs and support synergistic photothermal or photodynamic mechanisms for biofilm disruption and bacterial eradication. [21]

2. Anticancer Drug Delivery

Nanocarbon-based systems are extensively studied for anticancer drug delivery due to their capacity for targeted drug transport, enhanced tumor accumulation, and controlled release profiles. Studies show that carbon nanodots and functionalized graphene derivatives can improve the delivery of chemotherapeutic agents such as doxorubicin and other antitumor drugs, increasing local drug concentration within tumors while minimizing harm to healthy tissues. Their small sizes and modifiable surfaces enable enhanced permeation and retention (EPR) effects, as well as active targeting through ligand conjugation, ultimately improving therapeutic outcomes in cancers including colorectal carcinoma and oral cancers. [22]

3. Anti-Inflammatory and Chronic Disease Applications

Carbon-based nanocarriers are also being applied in anti-inflammatory drug delivery and management of chronic diseases. For example, carbon dots functionalized with bioactive polymers have been shown to deliver anti-inflammatory drugs (such as apremilast) effectively to inflamed tissues, improving uptake in macrophages and intestinal cells, which is particularly relevant for chronic inflammatory conditions like inflammatory bowel disease. Such nano-platforms can enhance drug bioavailability, target inflammation more precisely, and reduce systemic side effects. [21]
Moreover, the adaptable surface chemistry of carbon nanomaterials allows them to carry therapeutic agents for other chronic diseases, including diabetes and rheumatoid arthritis, broadening their clinical application potential beyond traditional antimicrobial and anticancer uses. [22]

4. Oral, Topical, and Injectable Formulations

Carbon nanocarriers are compatible with multiple administration routes, enabling versatile therapeutic delivery:
Oral delivery: Nanocarbon systems can protect drugs from degradation in the gastrointestinal tract, enhance mucosal penetration, and increase bioavailability — essential for chronic treatments and targeting diseases like colorectal cancer through oral formulations. [22]

Topical delivery: Nanocarbon carriers can be incorporated into gels, creams, or dressings for localized treatment of skin infections or inflammation, enhancing permeation and sustained release at the site of application. [24]

Injectable delivery: Intravenous or intratumoral injections of nanocarbon-based systems (e.g., functionalized CDs or CNT derivatives) enable precise systemic or localized delivery, improved circulation time, and the potential for image-guided therapy combined with therapeutic payloads. [21]

Opportunities in Developing Countries

Nanocarbon-based drug delivery systems (CNMs) hold special promise for developing countries because they can leverage affordable materials, bolster local production capacities, improve therapeutic outcomes, and contribute to global challenges like antimicrobial resistance (AMR).

1. Low-Cost Raw Materials and Local Production

One of the most compelling opportunities for developing countries lies in the use of low-cost and locally available carbon precursors—such as bio-waste and agricultural residues—to produce functional nanocarbon materials. Many developing regions produce abundant biomass (e.g., rice husk, coconut shells, and other lignocellulosic residues) that can be converted into activated carbon or graphene-like materials with minimal processing. Such bio-derived nanocarbons have been shown to retain high surface area and functionalizable surfaces suitable for drug loading and delivery, enabling cost-effective nanocarrier fabrication compared with more expensive synthetic carbon sources. [25]

This "valorization" of waste raw materials not only reduces material costs but also promotes local production ecosystems, stimulating entrepreneurship and technology transfer within resource-limited settings. Although specific biomedical applications are still emerging, the underlying material science groundwork supports the viability of this approach. [25]

2. Improvement of Drug Stability and Efficacy

Carbon-based nanocarriers such as carbon dots, carbon nanotubes, and graphene derivatives enhance the stability and bioavailability of loaded drugs—a major therapeutic advantage for many medications with poor solubility or rapid degradation. Scholarly reviews highlight that CNMs' high surface area and tunable surface chemistry protect drugs from premature degradation, improve circulation half-life, and improve therapeutic indices compared to conventional formulations. These properties can be crucial in settings where access to refrigeration and stringent storage infrastructure is limited. [17]

Additionally, studies demonstrate that CNMs can enhance intracellular delivery and targeted accumulation of therapeutics—such as anti-infective or antiviral drugs—resulting in stronger efficacy at lower doses. [26]

3. Reduction in Dosing Frequency and Side Effects

Nanocarbon carriers can be engineered for controlled and sustained drug release, which helps prolong drug circulation times and maintain therapeutic levels with fewer administrations. Such controlled release profiles reduce dosing frequency and improve patient adherence—benefits that are particularly impactful in low-resource settings where frequent clinical visits are challenging. In addition, localized delivery reduces systemic side effects, improving safety profiles compared to conventional drug formulations. [27]

This sustained release is particularly valuable for rural or underserved populations where frequent access to healthcare providers is constrained, and where missed doses can compromise treatment success.

4. Potential Role in Addressing Antimicrobial Resistance (AMR)

Antimicrobial resistance is a global health crisis disproportionately affecting lower- and middle-income

countries. Nanocarbon materials exhibit intrinsic antimicrobial properties and functions that help enhance the effectiveness of conventional antibiotics and potentially slow resistance development. A 2025 review underscores that CNMs such as graphene quantum dots, carbon dots, and functionalized carbon nanotubes show antibacterial activity against drug-resistant strains and impede bacterial growth through physical and chemical mechanisms that bacteria find difficult to evolve resistance against. [27]

Moreover, nanocarbon carriers can enhance antibiotic delivery to resistant pathogens, improve penetration into biofilms, and enable co-delivery strategies combining antibiotics with other agents to overcome resistance mechanisms. Reviews of nanomaterial-based antimicrobial strategies emphasize that such systems can improve drug solubility, targeted delivery, and therapeutic efficacy—key elements in mitigating AMR. [28]

Challenges and Limitations

While nanocarbon-based drug delivery systems (CNMs) demonstrate compelling advantages, their clinical translation—especially in developing countries—is hindered by multifaceted challenges and limitations. These issues span biological safety, regulatory frameworks, manufacturing scalability, and infrastructural constraints that must be addressed to enable safe and effective implementation. Below is an academically structured overview based on trusted scientific literature (post-2020).

1. Toxicity and Safety Concerns

A major barrier to clinical use of nanocarbon and other nanocarrier systems is potential toxicity and adverse biological responses. Nanomaterials can interact unpredictably with cells and tissues due to their size, surface chemistry, and particle composition. They may generate reactive oxygen species (ROS), disrupt cellular membranes, and cause inflammatory or immune responses, leading to cytotoxicity. Additionally, long-term accumulation in organs such as the liver, spleen, or kidneys is a serious concern due to persistent nanoparticle retention and unclear biodegradation pathways. Comprehensive toxicological studies—including in vitro, in vivo, and long-term exposure assessments—are essential but remain underdeveloped. [4]

Because of these complexities, thorough safety profiling and standardized biocompatibility evaluation protocols are crucial before CNMs can be translated into human therapies. [4]

2. Regulatory and Ethical Barriers

Regulatory frameworks for nanocarrier drug delivery systems are still evolving, and this uncertainty slows clinical approval and commercialization. The heterogeneous nature of CNMs poses a challenge for standard regulatory criteria that were originally designed for conventional small-molecule drugs. Key issues include inconsistent nomenclature, lack of universally accepted characterization methods, and difficulty defining quality control parameters unique to nanomaterials. Regulators such as the FDA and EMA are developing nanospecific guidelines, but comprehensive standards are not yet fully harmonized globally. [29]

Ethical concerns also arise related to risk communication, informed consent, and potential environmental impacts, underscoring the need for transparent reporting and public engagement to build trust. [30]

3. Scalability and Reproducibility

Translating CNM drug delivery successes from the laboratory to commercial-scale production remains a formidable challenge. Nanocarrier systems often require precise control of particle size, surface properties, drug loading, and release characteristics, which can vary widely with slight changes in synthesis

conditions. Ensuring batch-to-batch consistency is complex, and scalable manufacturing must preserve key physicochemical attributes without compromising safety or performance. [4]

Moreover, scaling up introduces additional costs and technical barriers, particularly where advanced equipment and stringent good manufacturing practices (GMP) are required. These constraints are often more acute in developing countries with limited industrial infrastructure. [4]

4. Infrastructure and Technical Expertise Limitations

Effective development, production, and clinical use of CNM-based systems require specialized infrastructure and multidimensional technical expertise in nanotechnology, pharmaceutical engineering, and regulatory science. This includes advanced characterization tools (e.g., electron microscopy, spectroscopy), controlled manufacturing environments, and trained personnel capable of implementing complex protocols for formulation, characterization, quality control, and safety testing.

In many developing regions, scarcity of such infrastructure and skilled workforce slows research progress and limits participation in global nanomedicine innovation—potentially widening the gap in access to advanced therapies. Investing in capacity building, training programs, and collaborative networks is therefore critical to overcome these barriers. [4]

Comparison with Conventional Drug Delivery Systems

Carbon-based nanocarrier drug delivery systems (NDDS), including nanotubes, graphene derivatives, carbon dots, and hybrid nanomaterials, are increasingly being compared with traditional drug delivery approaches (e.g., tablets, capsules, injection solutions) across key performance domains. Recent scientific reviews highlight significant differences and advantages of nanocarrier-based systems over conventional systems in terms of cost-effectiveness, therapeutic efficiency, and stability/storage requirements.

1. Cost-Effectiveness

While initial development and production costs for nanocarrier systems may be higher due to advanced materials and specialized manufacturing processes, nanocarriers can reduce overall healthcare costs in the long run. This cost-effectiveness arises because nanocarrier systems frequently:

Enhance drug bioavailability, allowing smaller doses to achieve therapeutic effects.

Reduce side effects and adverse reactions, lowering the need for additional treatments and hospitalization.

Improve patient compliance through controlled or sustained release formulations that reduce dosing frequency.

From a pharmacoeconomic perspective, these benefits can reduce downstream costs associated with traditional high-dose therapies, repeated hospital visits, and management of side effects. Such economic analyses suggest that although nanocarriers require investment, their overall impact on healthcare cost structures can be favorable. [31]

2. Therapeutic Efficiency

Nanocarrier systems offer enhanced therapeutic efficiency relative to conventional formulations due to several physicochemical and biological advantages:

Improved Solubility and Bioavailability

Conventional drug formulations often struggle with poor solubility and limited absorption in the body. Nanocarrier systems like liposomes, solid lipid nanoparticles, and polymeric nanocarriers can enhance solubility and intestinal uptake, leading to improved therapeutic levels of drugs that would otherwise be poorly absorbed. [32]

Targeted Delivery & Controlled Release

Nanocarriers enable both passive targeting (via enhanced permeability and retention at disease sites) and active targeting (through ligand conjugation), which increases drug accumulation at the site of action and reduces systemic toxicity. Controlled and sustained release profiles provide stable drug levels over extended periods, improving therapeutic outcomes and patient adherence compared to conventional systems that often exhibit rapid clearance and fluctuating plasma levels. [33]

Reduced Side Effects

By concentrating drugs at target tissues and minimizing off-target exposure, NDDS can reduce the incidence and severity of side effects that are common with traditional systemic therapies. This leads to better safety profiles and improved quality of life for patients. [33]

3. Stability and Storage Requirements

Conventional drug formulations such as tablets, solutions, and suspensions can be sensitive to environmental conditions (e.g., temperature, humidity), often requiring strict cold-chain storage or stabilizing excipients to maintain potency and shelf-life.

In contrast, nanocarrier systems—particularly those involving engineered carbon nanomaterials and lipid/polymer nanocarriers—can offer:

Enhanced protection of drugs from degradation prior to administration.

Improved chemical stability, as encapsulation shields active ingredients from enzymatic and environmental breakdown.

Flexibility in formulation, enabling stable liquid or solid formats with controlled release kinetics.

Although some nanocarrier formulations still require careful storage to preserve structural integrity (e.g., to prevent aggregation or loss of functional groups), their intrinsic stability advantages often surpass those of conventional drug forms by reducing premature degradation and maintaining therapeutic activity longer. [32]

Case Studies and Recent Advances (2020–Present)

Research in nanocarbon-based drug delivery systems has significantly progressed in recent years (2020–present), with several notable preclinical studies and formulation examples showing enhanced therapeutic outcomes, sustained drug release, and targeting capabilities compared with conventional drug delivery. These case studies demonstrate how carbon nanomaterials are being used as effective carriers in anticancer, antimicrobial, and multifunctional therapeutic applications.

1. Carbon Nanotubes and Graphene Derivatives in Cancer Therapy

Preclinical Evidence – Functionalized CNTs for Targeted Drug Delivery

Studies have shown that multi-walled carbon nanotubes (MWCNTs) can be functionalized to improve loading of anticancer drugs and sustain release under tumor-like conditions. In one study, carbohydrate-modified lysinated MWCNTs loaded with doxorubicin (a common chemotherapeutic) exhibited extended drug release over 120 h at acidic pH conditions, which mimics the tumor microenvironment, indicating potential for improved targeted therapy and reduced systemic toxicity. [34]

Graphene Nanocomposites for Anticancer Application

Graphene oxide (GO)-based nanocomposites functionalized with polymers and chemotherapeutic agents demonstrated enhanced cell uptake and prolonged release profiles in vitro. These systems also displayed antitumor mechanisms such as apoptosis induction and improved gene regulation in breast cancer cells—suggesting significant therapeutic potential in oncology research. [35]

2. Carbon Dots (CDs) for Multifunctional Delivery and Imaging

Carbon Dots in Theranostics (Therapy + Diagnostic)

Carbon quantum dots (CQDs) have emerged as promising theranostic nanocarriers—capable of integrating drug delivery, imaging, and diagnostics in one platform. Functionalized CQDs have been used for pH-responsive drug release and fluorescence imaging, enabling real-time monitoring of drug release and targeting of tumor tissues. Their biocompatibility and tunable surface chemistry make them versatile for anticancer applications and other therapeutic areas. [2],[36]

Antibacterial & Cancer Targeting with Carbon Dots

Specialized carbon dots have been formulated to deliver antimicrobial agents and exhibit anticancer effects with low toxicity, demonstrating inhibitory activity against bacterial growth and promising anti-tumor potential. These findings support carbon dots as a novel strategy in combating infections and cancer simultaneously. [37],[38]

3. Mesoporous Carbon Nanoparticles (MCNs) and Composite Formulations

Stimuli-Responsive Drug Delivery Platforms

Mesoporous carbon nanomaterials (MCNs) represent another class of nanocarbon carriers with high surface area, tunable pore structures, and stimuli-responsive release capabilities. These features allow for effective cargo loading and controlled release in response to environmental triggers (e.g., pH, temperature), making them suitable for targeted treatment strategies. MCNs have been investigated for in vivo imaging, photothermal therapy, and synergistic chemo-photo therapies, providing versatile platforms for preclinical nanomedicine researDebnat.[16],[39]

4. Integrated Drug Delivery and Diagnostics ("Theranostics")

Theranostic Nanocarriers

Recent reviews and experimental studies have highlighted the development of nanocarriers that combine drug delivery with diagnostic imaging. For example, carbon materials integrated with contrast agents and targeting ligands have shown selective accumulation in tumor tissues, offering not only therapeutic effects but also real-time monitoring capabilities that can significantly enhance treatment personalization. This approach underscores the potential of nanocarbon platforms to revolutionize both therapy and diagnosis simultaneously.[2] ,[40]

5. Broader Preclinical Support Across Multiple Carbon Nanomaterials

Comprehensive Evidence of Nanocarbon Performance

Comprehensive literature reviews summarize extensive preclinical evidence supporting the therapeutic efficacy of carbon nanomaterials—including CNTs, graphene, fullerenes, and carbon dots—in a range of drug delivery applications from anticancer therapy to antimicrobial and antiviral treatments. These studies highlight enhanced bioavailability, targeting, and combination therapies, indicating that carbon-based nanocarriers are among the most promising emerging vectors in nanomedicine research. [17],

Examples of Selected Successful Nanocarbon-Based Drug Delivery Formulations (Preclinical Studies, 2020–Present)

Key Insights from Recent Preclinical Evidence

Nanocarrier Type	Therapeutic Target	Key Findings	Source
Functionalized MWCNTs	Anticancer (Doxorubicin)	Sustained and pH-responsive drug release under tumor-like acidic conditions,	[34]

		enhancing therapeutic efficacy and reducing systemic toxicity	
GO-based Nanocomposites	Cancer Therapy	Enhanced cytotoxicity against cancer cells with controlled and sustained drug release compared with free drug	[35]
Carbon Quantum Dots (CQDs)	Theranostic (Anticancer & Imaging)	pH-responsive drug release with fluorescence imaging capability for real-time monitoring	[2]
Carbon Dots in Hydrogel	Antimicrobial (Cefadroxil)	Controlled antibacterial release with prolonged therapeutic activity and improved bacterial inhibition	[37]
Mesoporous Carbon Nanoparticles (MCNs)	Multi-modal Therapy (Chemo-photothermal)	High drug loading, stimuli-responsive controlled release and efficient photothermal conversion enabling synergistic therapy	[16]

- Preclinical efficacy: Carbon nanocarriers show controlled drug release, enhanced targeting, and improved therapeutic indices in cancer models and antimicrobial applications. [34]
- Multifunctionality: Carbon dots serve as both drug carriers and imaging agents, enabling theranostic applications. [2]
- Stimuli-responsive systems: Mesoporous carbon frameworks allow environment-triggered drug delivery with high loading capacity. [39]
- Diverse formulations: Nanocarbon platforms have been functionalized for various delivery routes (pH, photothermal, ligand-targeted), demonstrating broad applicability. [17]

Future Perspectives and Research Directions

Advancing carbon-based nanocarrier drug delivery systems requires strategic research and policy efforts that address sustainability, regulatory adaptation, and translational implementation—especially relevant for developing countries where resources are limited but health challenges are pressing.

1. Sustainable Nanocarbon Synthesis

Future research is increasingly emphasizing eco-friendly and sustainable synthesis methods for carbon nanomaterials to reduce environmental impact, lower production costs, and enhance biocompatibility. Recent studies highlight the use of renewable biomass waste and green chemistry principles to synthesize carbon quantum dots, graphene derivatives, and other nanocarbons using water-based processes without toxic chemicals. This sustainable production aligns with circular economy goals and may reduce hazardous byproducts associated with traditional methods, making nanocarbon preparation more environmentally responsible and suitable for broader application including biomedical uses. [41]

Despite progress, significant challenges remain—such as achieving high yields, maintaining uniform physicochemical properties, and scaling the green processes beyond lab scale. Continued efforts are needed to optimize biomass-derived nanocarbon synthesis pathways that are cost-effective, reproducible, and compatible with drug delivery performance requirements. [41]

2. Policy and Regulatory Framework Adaptation

Well-defined policy and regulatory frameworks are crucial to safely integrate nanocarrier technologies

into healthcare systems. Current nanomedicine regulation often lacks specificity for nanostructured carriers, leading to regulatory uncertainty and approval delays. Comparative analyses of frameworks in major regions (e.g., EU, US) reveal that while regulators have made progress in issuing guidance, coherent global standards tailored to nanotechnology-enabled medical products are still evolving. [42]

Addressing these gaps entails developing criteria that consider the unique properties of nanocarbon systems (such as size-dependent biodistribution and surface functionalization effects), refining safety and efficacy evaluation procedures, and fostering early dialogue between innovators and regulators. Harmonization of regulatory pathways across regions will help facilitate clinical adoption and global access, particularly if guidelines are designed to support adaptive evidence-based decision-making for emerging nanotherapeutics. [43]

3. Translation from Lab to Clinic in Low-Resource Settings

The transition of nanocarbon drug delivery systems from preclinical research into clinical application involves overcoming scientific, technical, and socio-economic barriers. Translational frameworks emphasize early integration of design strategies that prioritize biocompatibility, standardized characterization, and robust manufacturing practices, which can reduce clinical failure and accelerate product development. [44]

Key strategies include:

Interdisciplinary collaborations among chemists, biomedical engineers, clinicians, and regulatory scientists to refine nanoparticle design and preclinical models. [45]

Use of advanced predictive tools such as artificial intelligence (AI) and machine learning for optimizing nanocarrier properties and predicting biological interactions. [45]

Engagement with regulatory bodies early in the development process to align experimental design with safety and efficacy expectations. [43]

For low-resource settings, translating innovations requires capacity building, investment in infrastructure for characterization and safety testing, and frameworks that support local manufacturing and clinical trial capabilities. Policies that encourage public–private partnerships, research collaborations, and technology transfer can help bridge gaps between laboratories and clinics, democratizing access to nanocarbon-based therapies in regions where disease burden is high and conventional treatment options are limited. [44]

Conclusion

This review highlights the transformative potential of sustainable nanocarbon-based drug delivery systems as a next-generation solution for improving antimicrobial and pharmaceutical therapy, particularly in resource-limited settings. The key findings can be summarized as follows:

1. Sustainable Synthesis is Feasible and Essential:

Biomass-derived and green synthesis approaches (using agricultural waste, renewable precursors, and water-based processes) can produce high-quality nanocarbon materials with excellent drug-loading capacity, biocompatibility, and antimicrobial performance, while significantly reducing environmental impact and production costs.

2. Nanocarbon Systems Enhance Therapeutic Performance:

Carbon nanoparticles, graphene derivatives, and carbon quantum dots demonstrate strong potential as drug carriers by improving drug solubility, stability, controlled release, and targeted delivery. These properties are particularly valuable for antibiotics such as azithromycin, where resistance, poor bioavailability, and side effects remain major challenges.

3. Regulatory and Policy Gaps Remain a Major Bottleneck:

Despite strong laboratory evidence, the absence of harmonized, nanotechnology-specific regulatory frameworks continues to delay clinical translation. Current policies are not fully adapted to address the unique physicochemical and biological behavior of nanocarbon systems, highlighting the need for adaptive, evidence-based regulatory pathways.

4. Translation to the Clinic Requires Systemic Innovation:

Successful translation depends on early integration of sustainability, safety assessment, scalable manufacturing, and regulatory alignment. Interdisciplinary collaboration and context-specific translational strategies are critical to move nanocarbon technologies from the laboratory to real-world healthcare applications.

Implications for Healthcare Systems in Developing Countries

For developing countries, sustainable nanocarbon technologies offer a realistic and high-impact opportunity to strengthen healthcare systems:

Affordable and Local Production:

Using locally available biomass (e.g., agricultural waste such as wheat straw, rice husk, or sugarcane bagasse) enables low-cost, decentralized manufacturing of nanocarbon drug carriers, reducing dependence on expensive imported technologies.

Improved Access to Effective Therapies:

Nanocarbon-based formulations can enhance the efficacy of existing drugs, allowing lower doses, fewer side effects, and better patient adherence—critical for managing infectious diseases and antimicrobial resistance in low-resource settings.

Strengthening Research and Innovation Capacity:

Adoption of sustainable nanotechnology encourages capacity building in universities, hospitals, and research centers, fostering innovation, skilled workforce development, and South–South scientific collaboration.

Policy-Driven Health Equity:

By adapting regulatory frameworks and supporting translational research, governments can accelerate safe clinical adoption, ensuring that advanced nanomedicine benefits reach underserved populations rather than remaining confined to high-income countries.

Final Perspective

Sustainable nanocarbon drug delivery represents a convergence of green chemistry, nanotechnology, and global health policy. Its future success will depend not only on scientific innovation but also on regulatory reform, infrastructure development, and international cooperation. By aligning sustainability with clinical translation, nanocarbon technologies can become a powerful tool for achieving equitable, affordable, and effective healthcare in developing countries, ultimately contributing to stronger health systems and improved public health outcomes worldwide.

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