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Carbon nanomaterials derived from waste: Advancing sustainable agriculture for a greener future

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ABSTRACT

Carbon nanomaterials (CNMs) are sparking growing interest in sustainable agricultural practices due to their multifaceted applications. CNMs improve nutrient uptake, enhance soil health, and reduce environmental pollution. CNMs, such as carbon dots, carbon nanotubes, biochar, and graphene-based derivatives, can be synthesized from agricultural wastes and residues, industrial by-products, and food waste, through hydrothermal, pyrolysis, and other green methods. A circular economy is promoted by converting waste into valuable CNMs. They have distinctive physicochemical features, such as strong adsorption capacity, exceptionally high surface area, and inherent antimicrobial potential, which make them a valuable tool for preparing slow-release fertilizers, soil-improvement products, and pest control formulations. Several challenges still need attention, including clear risk assessment and regulatory guidelines, thorough toxicity evaluation, and scalable production to ensure safe and responsible use. This study highlights the fabrication of carbon-based nanomaterials using various waste resources, their unique properties, and their potential use in agriculture, and focuses on the need for sustainable farming practices. Future research should prioritize commercially viable and cost-effective production routes, assess long-term environmental impacts, and design a standardized protocol for their application. Integration of these innovative CNMs into agricultural systems would support greener, more efficient farming approaches, enhancing global food security and protecting the environment with minimal risk to humans and the environment.

Contribution/Originality: The review presents an integrated evaluation of waste-derived Carbon Nanomaterial synthesis, functional properties, and agricultural applicability within a circular economy framework, offering a consolidated perspective currently lacking in the literature.

1. INTRODUCTION

In the 21st century, global agriculture is facing major challenges like climate change, soil degradation, and declining water quality. These issues limit our ability to mitigate rising food demands for the growing global

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population. These issues need to be addressed on priority by exploring new materials and technologies supporting sustainable farming practices involving boosting crop productivity, improving soil health and fertility, and reducing impact on the environment (Ingrao, Strippoli, Lagioia, & Huisingh, 2023; Kumar et al., 2022; Padhan et al., 2025; Yuan et al., 2024). In an attempt to resolve these issues, carbon nanomaterials (CNMs) are offering encouraging solutions, providing a cost-effective and sustainable alternative in modern agriculture. The process of converting agricultural and industrial waste into valuable CNMs will help manage waste issues, providing advanced materials with remarkable physicochemical properties that can revolutionize agriculture (Sanoja-López et al., 2025).

The family of carbon nanostructures comprises multiple members, all of which share carbon atoms covalently bonded in a sp^2 hexagonal lattice. A two-dimensional (2D) graphene sheet serves as a versatile structural unit that can form a range of nanostructures, including 0D fullerenes, 1D single- or multi-walled carbon nanotubes (CNTs), and 2D graphene-derived materials, when folded in different ways. Other related nanomaterials include carbon nanohorns (CNHs), carbon nano-onions (CNOs), nanocones, and nanodiscs. Another versatile nanomaterial is nanodiamonds (NDs), which are different from other CNMs as they contain sp^3 bonding among carbon atoms (Abdelfatah, Hosny, Elbay, El-Maghrabi, & Fawzy, 2025). Recently, carbon dots have also gained attention due to their unique optical properties. Additionally, CNMs can also be assembled in the form of 3D-materials and superstructures (Abdelmonem et al., 2025; Flores-Contreras et al., 2024).

Carbon nanomaterials (CNMs), including graphene, biochar, CNTs, and carbon quantum dots, exhibit peculiar characteristics like larger surface area, chemical stability, high conductivity, and stronger adsorption ability, making them an ideal candidate for various agricultural applications such as water retention, soil conditioning, crop protection, and nutrient delivery. For example, biochar-derived nanomaterials improve soil structure, promote the activity of beneficial microbes, and increase nutrient retention. Graphene, as a nanomaterial, along with CNTs, is also reported to enhance nutrient uptake efficiency, water absorption, and assimilation in plants, and to increase crop productivity. Additionally, CNMs can adsorb and degrade hazardous agrochemicals, mitigating the negative impact of unnecessary fertilizers and pesticides used, promoting eco-friendly farming (Filik & Avan, 2020; Sharma, 2024).

The CNMs produced from agro-industrial wastes, such as biomass and organic waste, offer dual benefits: reducing environmental pollution and providing a sustainable route for their synthesis. Every class of CNMs has distinct properties, which are defined by their reactivity, size, and morphology (Abdelbary & Abdelfattah, 2020; Flores-Contreras et al., 2024; Talreja, Chauhan, & Ashfaq, 2025). CNMs generally exhibit better electrical conductivity, lower density, and higher mechanical strength, and can also undergo chemical functionalization, allowing us to tailor their properties for specific applications. It is subsequent that many studies have reported their multifaceted role in the medical field, mainly in oncology, cancer theranostics, and targeting the tumor environment (Hussain & Maktedar, 2023). Their use as a drug-delivery vehicle, platform for advanced imaging and sensing makes them easy to use in next-generation theranostics applications (Adorinni, Cringoli, Perathoner, Fornasiero, & Marchesan, 2021).

The solicitation of CNMs in precision agriculture is another promising possibility. Smart nanomaterials are being engineered to deliver pesticides and fertilizers with precision and sustained release, ensuring efficient resource use and reducing environmental contamination. CNMs, such as carbon quantum dots, are being investigated for their potential in targeted delivery systems to enhance the bioavailability of essential nutrients while simultaneously reducing nutrient losses via leaching. Incorporation of CNMs into sensors for real-time monitoring of plants and soil health enables farmers to make data-driven, informed decisions on-site. This helps farmers in the efficient and effective use of their resources (Thakur & Yadav, 2025; Yadav, Yadav, Ahmad, & Abd-Elsalam, 2023).

Even though the CNMs have shown promising potential in agriculture, several challenges, such as cost-effectiveness, large-scale production, and environmental safety, still persist. Synthesis of CNMs using waste materials still needs improvement to reduce energy consumption and minimize environmental impact. Another concern is their safe use in agriculture, which requires the development of comprehensive risk assessment frameworks. Current

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research is focusing on overcoming these issues by developing an eco-friendly, renewable, and biodegradable CNM aligning with the principles of green chemistry and circular economy (Rana et al., 2024). Figure 1 represents the diverse types of carbon-based nanomaterials used for agricultural purposes.

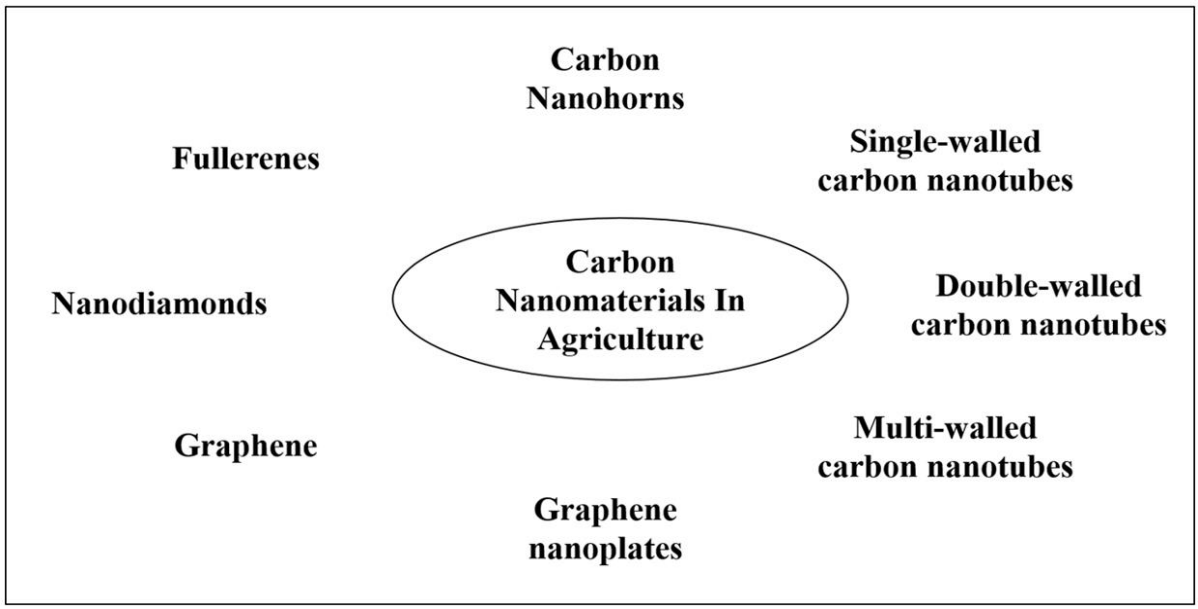


Figure 1. Types of carbon-based nanomaterials used in agriculture for various applications.

Use of CNMs derived from organic waste and incorporating them into modern agriculture practices would help in building a greener future, promoting resource efficiency, and simultaneously lowering carbon footprint in food production (Holka, Kowalska, & Jakubowska, 2022). However, a strong, supportive policy framework and interdisciplinary research would enable the widespread adoption of these novel CNMs. By harnessing the potential of waste-derived CNMs, more resilient and sustainable agriculture can be attained with secured food production (Mukherjee et al., 2016; Zhu, Chen, Gu, Ma, & Wu, 2022).

2. VARIOUS TYPES OF CARBON NANOMATERIALS

The innovative CNMs have emerged as a cutting-edge tool in modern agriculture for improving soil health, enhancing crop productivity, and strengthening pest management. These materials include fullerenes, graphene-based structures, carbon nanotubes, etc. CNTs enhance nutrient uptake and serve as carriers for agrochemicals, while graphene-based materials enhance water-holding capacity and disease resistance. Fullerenes exhibit antioxidant properties that protect plants against oxidative stress, and carbon quantum dots support bioimaging and plant growth monitoring. Other applications of biochar-based nanomaterials include carbon pounding and soil remediation, which is a result of their flexible properties, making them a suitable candidate for sustainable progression of agriculture (Adorinni et al., 2021). Some important classes of the CNMs are quoted here.

2.1. Fullerenes

These are spheroidal carbon-composed molecules, generally consisting of 60 carbon atoms, rendering them nanoscale and with electronic properties that make them promising for nanomedicine and drug delivery, photodynamics, antiviral therapy, and antioxidant potential. Fullerenes, as a distinct class of CNMs, have attracted significant attention for agricultural use due to their stability, antioxidant activity, and high surface area. These spheroidal NMs protect plants from biotic and abiotic stresses, improve growth, and nutrient intake. In addition to fullerenes, their derivatives are also explored for their function in soil remediation, snowballing photosynthetic efficiency, and controlled release of agrochemicals. Despite their advantages over chemical counterparts, it is

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imperative to understand the environmental and long-term impacts of these CNMs on plant health and soil microflora (Kerna & Flores, 2020; Singh et al., 2024).

2.2. Carbon Nano-Onions (CNOs)

Carbon nano-onions (CNOs) are fullerenes with multi-layered CNMs that have attracted attention for biomedical applications in bioimaging, sensing, and drug delivery, owing to their biocompatibility. They can outshine other CNMs for their ability to act as a terahertz contrast agent in breast cancer imaging (Bartkowski & Giordani, 2021). Their remarkable properties, such as electro-thermal conductivity and surface functionalization, make them appealing for agricultural purposes. CNOs are great crop productivity boosters, act as smart agrochemical carriers, and function as powerful antioxidants, helping plants deal with oxidative stress. Their ideal application in precision farming, controlled nutrient release, and plant disease management underlines their use in sustainability (Das, Panigrahi, Ghosh, & Tripathi, 2024; Soylukan, Yesıldal, & Akyüz, 2025).

2.3. Carbon Quantum Dots (CQDs)

Carbon quantum dots (CQDs) are quasi-spherical NPs widely recognized for their luminescent properties, demonstrating high applicability in sensing and related applications. Some morphological advancements have been made to improve their optical properties, which are the functions of the chosen carbon precursor material. CQDs are also used in photodynamic antimicrobial therapies, various bioimaging modalities, radiolabelled imaging, and diagnostic applications. CQDs are also explored for their antioxidant property against ROS-induced cellular damage, and for using them as potential drug-delivery vehicles (Azam, Najabat Ali, & Javaid Khan, 2021; Qureshi, Dabash, Ponnamma, & Abbas, 2024).

2.4. Nanodiamonds (NDs)

Nanodiamonds differ from other nanostructures in containing sp3 – hybridized carbon atoms. They also contain sp2 hybridized carbon atoms and some surface functional groups, which can be explored for the chemical modification (Kaur & Badea, 2013; Nunn, Torelli, McGuire, & Shenderova, 2017). NDs are recognized for their role in enhancing plant stress tolerance, promoting seed germination, and mitigating environmental contamination by reducing excessive agrochemical use. Their budding applications in precision agriculture and sustainable farming practices make them an innovative tool for refining crop productivity while minimizing ecological impact (Thekkedath & Sridharan, 2022; Torres, Holban, & Gestal, 2019).

2.5. Carbon Nanohorns (CNHs)

Carbon nanohorns (CNHs), also known as nano-cones, contain sp2-hybridized carbon atoms arranged in clusters of roughly 100 nm in diameter. They generally occur in two forms, one is 'bud-like' where cones are enclosed, and 'dahalia-like' where cones radiate outward from the aggregate. These are typically fabricated through processes such as laser ablation, joule heating, and arc discharge. Though the alternative, cost-effective, low-temperature methods are being sought. Like other CNMs, CNHs are also explored for applications like drug delivery, sensing, theranostics, and as components of nanocomposites of phosphoproteomics in cancer diagnosis and therapy, as well as developing topical coatings for skin application (Murata et al., 2001; Pagona, Tagmatarchis, Fan, Yudasaka, & Iijima, 2006). CNH's ability to adsorb and deliver various agrochemicals, such as fertilizers and pesticides, enhances efficiency and reduces environmental impact by mitigating leaching and volatilization. CNHs also exhibit antimicrobial properties, helping protect crops from pathogens and promoting healthier plant growth. Additionally, they can be applied in soil remediation, where they adsorb pollutants and heavy metals, improving soil quality. CNHs could play a critical part in sustainable agricultural practices, enhancing productivity while reducing chemical inputs (Furmaniak, Gauden,

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Patrykiejew, Miśkiewicz, & Kowalczyk, 2018; Kagkoura & Tagmatarchis, 2020; Le, Lerkprasertkun, Sano, Wu, & Charinpanitkul, 2023; Pandit, Alam, Javed, Waziri, & Imam, 2023).

2.6. Carbon Nanotubes (CNTs)

Carbon nanotubes (CNTs) are visualized as rolled graphene sheets and are categorized into single-walled and multi-walled depending upon the number of layers present in the structure. Like other CNMs, these CNTs are also regarded as promising candidates for advancement in the biochemical field. On the contrary, their structural similarity to asbestos particles raises concerns about limitations to their broader applicability and safety. These issues can be overcome by certain surface functionalization processes (Gupta, Gupta, & Sharma, 2019; Ijaz et al., 2023; Patel, Kim, Dutta, Ganguly, & Lim, 2020). CNTs were added to the ChemSec SIN (Substitute In Now) list in 2019 due to concerns such as their documented toxicity and limited biodegradability. This prompted immediate responses from the research groups working on CNTs, who feared hindrance to future research. Further research in the field demonstrated that the toxicities are related to specific types of CNTs, and, as a broader class, it is highly diverse, with biocompatibility affected by numerous factors, such as route of administration and surface functionalization. CNTs show significant promise in sustainable agriculture, including applications like enhancing growth promotion and seed germination, stress tolerance, and also hold applicability in gene delivery and biosensing (Patel et al., 2020). Studies have demonstrated that CNTs can promote seed germination and seedling development across different crop varieties. CNTs are reported to boost photosynthetic efficiency and chlorophyll content, resulting in improved vegetative growth. CNTs can modify the flexibility, permeability, and lipid content of the plasma membrane in roots, thereby facilitating greater water uptake and transport, thereby benefiting crops under stress conditions. They can also modulate the reproductive growth of ornamental plants and fiber-producing plants by promoting flower production (Adorinni et al., 2021; Safdar et al., 2022).

2.7. Graphene-Based Materials

Graphene-based materials belong to a diverse family of nanomaterials, making it essential to identify the specific structures under discussion and understand how they differ from those reported in previous studies. Graphene-based NMs have multiple applications in the medical sciences; most prominently, their antimicrobial activity is particularly useful for this purpose. Despite ongoing research, many challenges limit its applicability for large-scale industrial use and its transformation into multipurpose, widely available commercial products. These are important for sensing applications due to their distinctive 2D structures. Their applicability across various fields is continually increasing as their properties, such as biocompatibility, are further studied and revealed. Though these materials occur in different forms, discussing their implications and the simultaneous elimination of their toxic effects is imperative. For this, one of the most important aspects is to study the biomolecular coronas that form on the surface of the graphene, which influences their compatibility with living cells and their biocompatibility (Adorinni et al., 2021; Antunes, 2023). Their antimicrobial properties also benefit in plant disease management by eliminating harmful pathogens. Graphene-based sensors are established for real-time monitoring of crop conditions and soil health, enabling safer, more precise agriculture. Further studies are necessary to assess their environmental impact and ensure their safe and sustainable use in agricultural systems (Kumari, Rana, Yadav, & Kumar, 2023; Sharma et al., 2025; Ur Rahim et al., 2021; Yaragalla, Bhavitha, & Athanassiou, 2021).

2.8. Biochar-Based Nanomaterials

Nanostructures derived from biochar are emerging as promising functional materials for diverse applications such as energy storage, environmental remediation, and biomedicine. Biochar is prepared by thermal decomposition of biomass under oxygen-deprived conditions. It is a highly porous structure with rich functionalities and tunable physicochemical properties. Biochar can be transformed into a functionalized material with processes such as doping,

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chemical activation, hybridization with other materials, and imparting enhanced properties like adsorption, conductivity, and catalytic activity. Biochar offers a sustainable, cost-effective substitute for traditional materials, particularly for heavy metal removal, carbon-based electrodes, and drug delivery systems (Bhandari et al., 2023; Damahe, Mayilswamy, & Kandasubramanian, 2024; Nosratabad, Yan, Cai, & Wan, 2024). Nanobiochar is a widely emerging, attractive material for agricultural use, applied to increase soil fertility, enhance water retention, and boost crop productivity. Its porous nature and high surface area enable slow release of entrapped materials like agrochemicals and improve nutrient adsorption and absorption in plants (Brar et al., 2024; Chausali, Saxena, & Prasad, 2021; Mazarji et al., 2023; Sheokand et al., 2023; Wang et al., 2022).

3. COMPOSITION OF ORGANIC BIOMASS

Biomass is a widely available organic matter originating from many sources that include perennial trees, agricultural residues, household wastes, by-products of fishery and poultry, forestry and animal husbandry, and many related industries. Yet biodegradable and complex, biomass is composed mainly of lignin, cellulose, and hemicellulose, as well as some proteins and other minor components. With respect to plant-based biomass, 30-60% is cellulose, 20-40% is hemicellulose, and 15-25% is lignin. Being abundant, renewable, harmless, and eco-friendly, biomass serves as an excellent source of carbon for the production of CNMs. Unfortunately, a large amount of this biomass is burnt, landfilled, and discarded. As a result of these practices, valuable resources are converted into pollutants, posing risks to human and environmental health. Recently, researchers have been focusing on the development of new methods for the biomass conversion into useful CNMs, thus transforming environmental burden into valuable resources (Kang, Huang, Yang, Yan, & Chen, 2020). Figure 2 illustrates the different types of waste available for the synthesis of carbon-based nanomaterials.

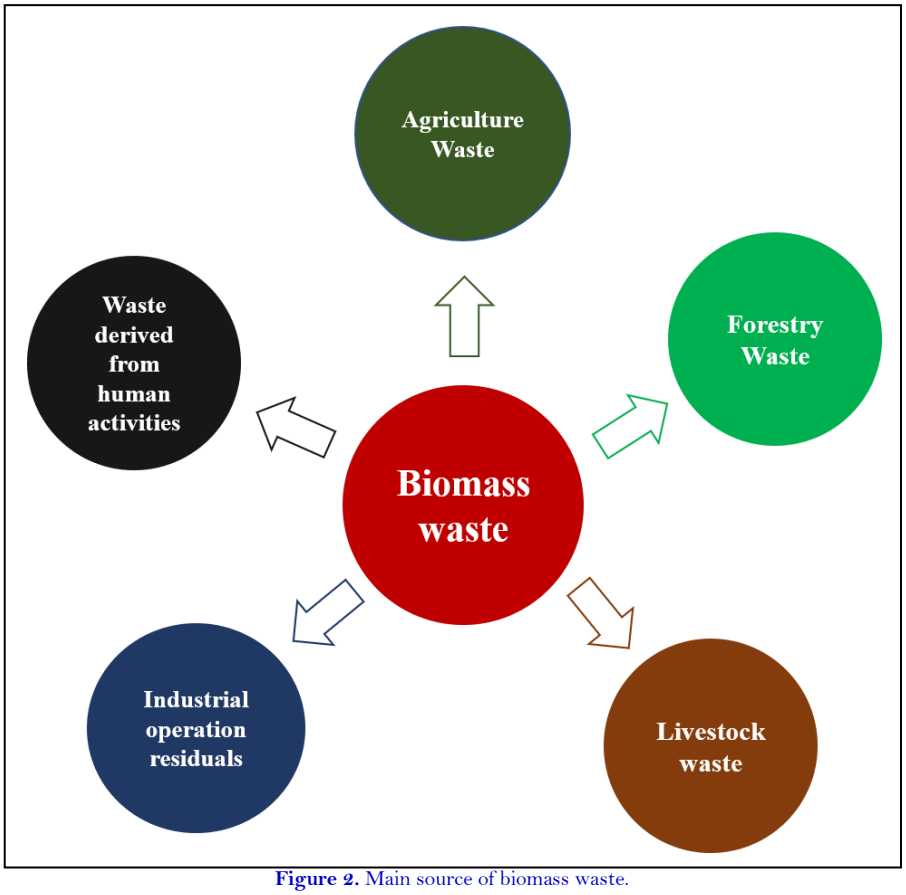


Figure 2. Main source of biomass waste.

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3.1. Biomass to Carbon-based Nanomaterials Synthesis

Biomass waste desirably originates from plant photosynthesis that includes materials such as wood-based plant matter, wastewater-derived deposits, and agricultural residues. These wastes are important with respect to both producing sustainable energy resources, such as biofuels, and as a source of carbon-rich feedstock for the generation of high-value CNMs. For example, Sun and coworkers have successfully converted coconut shells into porous graphene nanosheets, demonstrating the repurposed utilization of plant-based waste materials for the fabrication of advanced nanomaterials. Here, the coconut shells (~3g) and $ZnCl_2$ (~9g, activating agent) were mixed with $FeCl_3$ solution (~50mL, 3M, catalyst precursor). Carbon precursor was collected following evaporation (~80℃, 2hrs) and drying step (~100℃) of the mixed solution. The following step was to heat the carbon precursor (~900℃, 1hr) in a tube furnace under N_2 atmosphere to obtain graphene nanosheets (Deng, You, Sahajwalla, & Joshi, 2016; Sun et al., 2013).

Primo and colleagues have demonstrated the innovative use of shell waste from crustaceans for the extraction of chitosan and for the synthesis of N-doped graphene without a catalyst. They initially prepared a spin-coating of chitosan, followed by annealing the film at 200 °C for two hours under an inert argon atmosphere. Finally, the films were pyrolyzed at 600 – 800 °C under oxygen-free conditions. As a natural component of chitosan, nitrogen acts as an intrinsic dopant, introducing N atoms into the graphene structure. Doping enhanced graphene's electronic properties, enabling its application in electronic devices. They were also able to prepare the thin monolayered graphene sheet with exceptionally high transmittance, i.e., more than 99 percent (Primo, Atienzar, Sanchez, Delgado, & García, 2012).

4. FABRICATION OF CARBON NANOMATERIALS FROM ORGANIC WASTE

In recent years, organic biomass such as wood, leaves, and plant husks has been used to produce CNMs via green synthesis. This green synthesis reaction using organic biomass, depending on reaction conditions and precursor material, yields different forms of carbon nanoparticles, such as nanofibers and nanotubes. A study group developed graphite carbon nanostructure by precipitation technique at 900 °C by using cellulose as a starting material, with hydrothermal treatment (Sevilla & Fuertes, 2010). In another study, carbon nanostructures were developed from cellulose (husk) by an acid digestion process followed by a pyrolysis reaction (Herring et al., 2003). Other sources for green synthesis of CNMs include plants and microbes like fungi and bacteria. These sources are termed green sources as they are less energy-consuming and environment-friendly too.

4.1. Biosynthesis of Carbon Nanomaterials from Microorganisms

Microorganisms present in soil and water can attract and react with ions in their immediate surroundings, converting them into elemental metal through enzymatic reactions. These reactions may occur intracellularly, where ion fluxes into the microbial cell play a major role, or extracellularly, where the ions in the immediate environment get adsorbed on the microbial cell wall and get reduced to metallic ions in the presence of enzymes (Zhang, Yan, Tyagi, & Surampalli, 2011). The major factors that affect the biosynthesis from microorganisms are temperature, strain of microbes, pH, static or shaking conditions, and substrate concentration and type (Wei et al., 2021). However, it is important that microbes used for biosynthesis should be non-pathogenic in nature (Ahmed et al., 2021).

4.1.1. Biosynthesis from Bacteria

Bacteria undergo respiration, in which they reduce metals, acting as catalysts in biosynthesis. During this respiration process, electrons move from reduced organic to oxidized form, yielding crystal structures. This process was majorly seen in genus *Shewanella* by Kim, Kim, Lee, and Hur (2018) where bacterial nanowires and flavins were excreted through the bio-reduction process (Kim et al., 2018). This ability to reduce heavy metal ions and form nanoparticles was also seen in *Pseudomonas* Sp. (*stutzeri* and *auerginosa*) which, when exposed to heavy metals, resorts

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to self-defense mechanisms to overcome toxicity and yields nanoparticles. Many prokaryotic bacterial species are used for metal oxide and metal nanoparticles synthesis, like Enterobacter, Klebsiella, and Morganella Sp. Recently, Titanium dioxide nanoparticles were reported from *Lactobacillus* and *B. subtilis* Sp. (Gobinath et al., 2021).

4.1.2. Biosynthesis from Fungi

Compared to other microbes, fungi are relatively easy to cultivate, making them more suitable for biosynthesis. Furthermore, fungi have higher tolerance to metals because of the presence of chitin in their cell wall, along with their ability to secrete larger quantities of extracellular protein secretions, which stabilize the nanoparticles (Iravani, Korbekandi, Mirmohammadi, & Zolfaghari, 2014). Many filamentous fungi, like *Fusarium oxysporum* and *Verticillium* Sp, have the potential to biosynthesize Ag and Au nanoparticles as they have a significant amount of proteins and secondary metabolites that stabilize the nanoparticles. It has been observed that different strains yield different nanoparticles. For example, *Verticillium* species yield cubo-octohedral shapes while *F. oxysporum* yields quasi-spherical shapes (Senapati, Ahmad, Khan, Sastry, & Kumar, 2005). Also, by altering the ion ratio in the biosynthesis reaction, alloy and metal nanoparticles can be produced. Thus, by manipulating the type of strain, one can obtain nanoparticles with different properties (Sun & Xia, 2002).

4.1.3. Biosynthesis of Carbon Nanomaterials from Plants

Using organic biomass, which not only serves as a precursor for CNM biosynthesis but also as a catalyst for the biosynthesis reaction, has particular advantages. These catalysts and precursors are available abundantly in nature and have the ability to operate at lower processing temperatures, with noncomplex equipment, and non-toxic byproducts (Tripathi, Pavelyev, & Islam, 2017).

4.1.3.1. Carbon Nanotubes (CNT)

Chen, Timpe, Hamid, Schlögl, and Su (2009) employed palm kernel shell, wheat straw, and coconut, which contained iron as an impurity, as a catalytic agent for CNT production (Chen et al., 2009). In another instance, Camphor extracted from the latex of the cinnamon tree (*Cinnamomum camphora*) was used as a precursor, along with zeolite or quartz catalyst, when impregnated with Fe-Co at a temperature of 650 °C or above, yielding a high amount and purity of MWCNTs (Kumar & Ando, 2007). Walnut extracts have also been used through the CVD process to yield carbon nanobelts at 800 °C. Recently, rice husks containing cellulose and lignin have also been employed as an ideal source for CNP synthesis using a microwave-assisted process, where ferrocene was used to enhance the RH decomposition (Asnawi, Azhari, Hamidon, Ismail, & Helina, 2018).

4.1.3.2. Carbon Quantum Dots (CQDs)

Fluorescent CQDs were obtained from fruit and plant extracts like pomegranate peel, willow extract, beet root, etc. Recently, a coconut milk byproduct during pyrolysis, which generally contains a high amount of saturated fats, was used for obtaining CQDs (Preethi, Viswanathan, & Ponpandian, 2021). Here, pH and temperature were shifted to obtain blue-emitting CQDs for detecting Fe3+ in coconut milk. Similarly, low-cost hydrothermal treatment of leaf extracts obtained from neem (*Azadirachta indica*) yielded high fluorescent CQDs (Zhou et al., 2013). Other precursors for fluorescent CQDs were *Tamarindus indica* leaves, sweet potato peels, red chilli, black paper, cinnamon, etc. Wei et al. (2021) also employed *Gynostemma* as a starting material to obtain fluorescent carbon dots by pyrolysis, which was further formulated as CDs/AgNPs composite and evaluated for their antibacterial efficiency (Wei et al., 2021).

4.1.3.3. Graphene

For the biosynthesis of graphene from plant sources, graphene oxide is reduced to obtain graphene nanosheets. Kim, Kim, and Min (2011) reduced graphene oxide using dextran as a precursor to obtain graphene (Kim et al., 2011).

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Similarly, triethylamine, amino acid glycine, along with *Ginkgo biloba* extract, have been reported in the last few years as reducing agents for the synthesis of graphene (Gurunathan, Han, & Kim, 2013).

4.1.3.4. Wastewater and Bio-Sludge

Wastewater effluents and industrial sludge are recognized as prominent cradles of valued metals and metal oxides. Thus, the waste effluents are comprehensively studied for the retrieval of materials like lead oxide (PbO), Co, Ni, Cu, Mo, silicates (SiO_2), Silver (Ag), rare earth metals, platinum (Pt), etc. Whereas the concentration of the trace elements is extremely flexible amid waste effluents, they are associated with the explicit activities executed in the emitting source, and the mineralogical diversity established within a single source of effluent. The U.S. Geological Survey has acknowledged Ga and in present in waste effluents from Zn ore mining. Through biosolid mining and wastewater, Ga and In are recovered and recycled for the production of integrated circuits, photodetectors, light-emitting diodes (LEDs), solar cells, and semiconductors (Smith, Hageman, Plumlee, Budahn, & Bleiwas, 2015). An elemental examination of waste torrent samples (e.g., mining influenced waters) from various historical metal mining sites found concentrations of Os (Mdn. ~0.02 ppm), Ir (Mdn. ~0.001 ppm), La (Mdn. ~20 ppm), Ce (Mdn. ~40 ppm), Nd (Mdn. ~20 ppm), Ag (Mdn. ~10 ppm), Au (Mdn. ~0.3 ppm), Pd (Mdn. ~30 ppm), Pt (Mdn. ~1 ppm), Re (Mdn. ~ 0.01 ppm), Sm (Mdn. ~4 ppm), Gd (Mdn. ~4 ppm), Ga (Mdn. ~15 ppm), In (Mdn. ~ 1 ppm), Sb (Mdn. ~10 ppm), Yb (Mdn. ~2 ppm), Th (Mdn. ~4 ppm), Zn (Mdn. ~1,000 ppm), Cu (Mdn. ~150 ppm), and Te (Mdn. ~1.5 ppm). Though recovery of some of these metals might not always be economically viable, extraction and reclaiming trace elements from wastewater streams can still assist in offsetting treatment and disposal costs. Most significantly, it can minimize the risk to both public health and the environment (Smith et al., 2015). Urbina and colleagues presented an innovative and creative strategy for the recovery of metals from aqueous waste generated during biomining and bioremediation. They developed the methods involves metal-binding peptides for fungal mycelium functionalization, selectively capturing the metals. To support these approaches, in silico models were developed that were capable of predicting the strength of binding metals and natural ligand-binding motifs. These models counted their valued contribution as they were generated using the open source software and databases like the Protein Data Bank for the analysis of structural characteristics of metal within metalloproteins. They concluded with the successful design of peptides having strong and selective bonding ability with copper, presenting a high correlation between motifs those generated computationally and those that are naturally occurring (Urbina et al., 2019).

4.1.4. Waste Vegetables and Animal Oil for CNTs Synthesis

Oils from different sources like eucalyptus, coconut, palm, neem, and turpentine contain a certain amount of carbon, making them a favoured feedstock for the generation of high-purity (90%) CNTs (carbon nanotubes). Out of these, palm oil ($C_{55}H_{100}O_6$) stood out for the production of high-quality CNTs because of its relatively low H-content, which helps in minimizing the formation of amorphous carbon. Suriani and co-workers demonstrated this CNT formation by preparing vertically aligned CNTs, i.e., VACNTs, using waste from cooking palm oil. The experiment involved a floating catalyst CVD system comprising two alumina tube furnaces. The filtered palm oil was mixed with ferrocene (5.3 wt%) and kept in an alumina boat in the centre of the furnace. On the other hand, a cleaned silicon substrate was positioned in the centre of the second furnace. Following the preheating of the substrate furnace to 750 ^oC under argon atmosphere, the palm oil furnace was heated to 450 ^oC for 30 min, which allowed the breakdown of oil into hydrocarbon molecules. In this process, ferrocene served as a catalyst with dual function, i.e., facilitated the deposition of palm oil and acted as a promoter for CNT (Suriani et al., 2013; Suriani, Nor, & Rusop, 2010).

After successful synthesis of VACNTs using waste cooking palm oil, the work was extended by Suriani and coworkers, where they explored animal oil sources as an alternative for carbon. Poultry processing produces an abundant amount of poultry fat, which was selected as a raw material. Chicken fat also contains a high content of carbon and has a low carbon-to-hydrogen ratio, proving its suitability for CNTs synthesis. They first extracted the

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oil by heating the chicken fat, followed by the addition of ferrocene catalyst (5.33 wt%). Mixture was placed in a CVD system and followed the same procedure previously used with furnace heating temperature at 470 °C and time extended to 60 min. They produced VACNTs with excellent crystallinity and high purity (88.2 %) (Deng et al., 2016; Suriani et al., 2013).

5.APPLICATIONS OF WASTE-DERIVED CARBON-BASED NANOMATERIALS IN AGRICULTURE

Waste-derived CNMs are a recent source of interest for affordable, sustainable improvements in agricultural production. Biochar, graphene, and carbon dots are derived from domestic waste, industrial effluents, and agricultural residues. This transformation helps in lowering pollution and offers benefits in multiple aspects (Kainth, Sharma, & Pandey, 2024; Mubarik et al., 2021). One of the key applications of these CNMs is in soil remediation through improving soil structure, heavy metal removal, increasing water retention capacity, and reducing soil contamination and pollution (Nie, Huang, Li, Lu, & Ling, 2024; Priya, Muruganandam, Ali, & Kornaros, 2023; Yan et al., 2020). Table 1 summarizes a few of the bio-waste-derived CNMs and their application in agriculture.

Table 1. CNMs derived from bio-waste and their application in agriculture.

Type of Bio-derived waste	Type of CNMs	Application	References
Salicornia ramosissima	Cellulose nanofibers	Reinforcing agent	Lima, Cristofoli, da Costa, Saraiva, and Vieira (2023)
Potato peel	Cellulose nanoparticles	Active packaging	Ramesh and Radhakrishnan (2019)
Oil palm waste	Cellulose nanofibers	Preparation of bioaerogel scaffold	Yahya, Khalil, Ahmad, Rizal, and Muhammad (2023)
Rice husks, oat husks, and oat straw	Silicon carbide nanostructures	Efficient co-electrocatalysts for water splitting	Nikitin et al. (2024)
Red onion peels, kepok banana peels, banana leaves	Nanocellulose	Wound healing, tissue regeneration	Datta et al. (2025) and Manurung, Yakosati, Putri, and Suciyati (2024)
Orange peels, sugarcane bagasse, Rice bran	Graphene oxide NPs	Soil remediation Strong antimicrobial agents	Bytešníková et al. (2022); Hashmi, Singh, Jain, and Singh (2020) and Yan et al. (2024)
Sugarcane Bagasse	Graphene oxide NPs; Carbon quantum dots	Plant growth promoters Seed priming agents	Baweja and Jeet (2019); Farhangi-Abriz et al. (2025) and Maholiya et al. (2023)
Rice husks	Graphene quantum dots	Nano biosorbent	Mahmoud, Fekry, and Abdelfattah (2020)
Black mulberry fruit pulp	Black mulberry encapsulated carboxymethyl cellulose/ silica nanoparticles	Antibiotics against *Staphylococcus aureus*, *Escherichia coli*	Sharifi and Pirsa (2021)
Groundnut shell	Carbon nanoparticles	Development of nano fertilizers and nano pesticides; Pollution remediation; Energy storage	Farmand et al. (2022) and Yallappa et al. (2017)

Carbon-based nanomaterials can act as nano-fertilizers, supplying essential nutrients and boosting plant metabolism, leading to improved crop yields. Their antimicrobial properties also make them effective in protecting plants against pathogens, reducing the dependency on synthetic pesticides. Furthermore, CNMs contribute to carbon sequestration, serving to mitigate climate change influences. As research progresses, integrating these nanomaterials into precision agriculture could revolutionize sustainable farming practices, making agriculture more efficient, eco-

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friendly, and resilient to environmental stressors (Toplicean & Datcu, 2024). Table 2 summarizes various applications of waste-derived carbon-based nanomaterials in agriculture and farming.

Table 2. Various types of carbon-based nanomaterials and their applications in agriculture.

Type of CNMs	Dose/Concentration	Catalytic activity	References
CNT + chlordane components; CNT + DDE	1000 mg/L for 19 days in lettuce	Non-functionalized CNT was more effective at reducing the organochlorine accumulation by plant roots (88%) and shoots (78%).	Hamdi, De La Torre-Roche, Hawthorne, and White (2015)
Carbon nano-horns (CNHs)	25, 50, and 100 mg/ml for 10–20 days barley, corn, rice, soybean, switchgrass, tomato) and tobacco cell culture	The growth of tobacco cells was increased 78%. Uptake confirmed by TEM.	Lahiani et al. (2015)
Water-soluble CNPs	10–150 mg/L ws-CNPs in soil up to 20 days	Optimum growth was observed at 50 mg/L treatment, where root and shoot lengths were increased up to 3-times.	Saxena, Maity, and Sarkar (2014)
Carbon nano-dots	10 days of exposure to 150 mg/L water-soluble carbon nano-dots	Enhanced root growth (10x) of wheat.	Tripathi and Sarkar (2015)
Fullerols $C_{60}(OH)_{20}$	0.943, 4.72, 9.43, 10.88, and 47.2 nM fullerol	Increased plant biomass and phytomedicine content in bitter melon.	Kole et al. (2013)
MWCNTs	5–60 mg/L MWCNTs for 7 days in agar gel	60 mg/L treatment; increased plant fresh biomass (43%) and higher nutrient uptake (2x calcium and 1.6x iron)	Kumar and Ando (2007)

5.1. Future Perspectives

The CNMs derived from waste materials hold great promise for agriculture and many other fields. They offer innovative pathways towards addressing global food security while promoting environmental stewardship. By recycling the organic and agricultural waste into advanced soil amendments and targeted delivery systems, CNMs addresses pressing issues of waste accumulation and transforms them into valuable output. These nanomaterials, such as CDs and CNTs, can minimize the leaching of synthetic fertilizers into waterways, increase nutrient uptake efficiency, and reduce greenhouse gas emissions associated with conventional agricultural practices. Their inherent properties make them useful as gene and agrochemical carriers, thus fostering a healthier ecosystem.

The next generation of CNMs holds promise of developing regenerative and circular agricultural systems. New avenues are focusing on leveraging these CNMs to improve plant resilience against various stresses, such as salinity, diseases, and drought, likely through improved soil quality and plant signaling pathways. The energy consumption for producing these NMs is lower than for conventional NMs, and the processes are economically viable. The future research must orient efforts towards developing a closed-loop system where waste is continually recycled into high-value end products that up-scales production, soil quality, and aids in operational harmony with the natural carbon cycle.

6. CONCLUSION

In conclusion, these CNMs derived from waste represent a significant opportunity for sustainable agricultural advancements. The transformation of waste into valuable resources imposes dual benefits, i.e., crop improvement and

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mitigation of environmental pollution issues. This demonstrates that ecological responsibility and agricultural productivity can go hand in hand. Ultimately, the development of these waste-derived CNMs is poised to play a critical role in shaping the future of agriculture. Continued research and development would be needed to optimize the synthesis and application of these materials, paving the way for their widespread realization and full potential, creating a largely sustainable, environmentally conscious agricultural landscape.

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