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Review Article

The potential contribution of nanocarbon to fostering sustainable agriculture for future generations

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ABSTRACT: Nanocarbon materials, with their size and unique properties, have found a range of uses in agriculture. These uses include improving soil quality, managing nutrients, controlling pests, purifying water, and monitoring crop growth. Nanocarbon materials help improve the structure of the soil and retain nutrients, creating an environment where plants can thrive. They also serve as carriers for controlled nutrient release and promote plant development. In pest management, nanocarbon-based formulas deliver pesticides or helpful microorganisms with precise targeting to minimize environmental harm. When it comes to water purification and bioremediation, nanocarbons' ability to adsorb contaminants makes them a valuable tool for cleaning water sources. Additionally, nanocarbon is used in crop monitoring systems that provide real-time information on plant health and environmental conditions, helping farmers optimize their practices. However, for nanocarbons to be widely adopted in agriculture, safety concerns must be addressed, along with approvals and cost-effectiveness considerations, to ensure their integration into farming methods.

KEYWORDS: nanocarbon; monitoring crop growth; pest management; controlled nutrient release; water purification; bioremediation

1. Introduction

Nanocarbon is a term used to describe various forms of carbon-based nanomaterials that have unique properties due to their small size and structural characteristics. These materials are composed primarily of carbon atoms and can take on different forms. **Table 1** provides an overview of various types of nanocarbon materials, their structures, and some of their key properties and applications. It's important to note that each type of nanocarbon has its own distinct characteristics that make it suitable for specific applications.

Table 1. Different types of nanocarbon materials.

Type of nanocarbon	Structure	Properties and applications
Carbon nanotubes (CNTs)	Cylindrical tubes	High mechanical strength, electrical conductivity, used in composites, sensors, and electronics, little refractive index (n~1.1).
Graphene	Single layer of carbon atoms arranged in a 2D hexagonal lattice	Exceptional electrical, thermal conductivity; used in electronics, sensors, composites, and energy storage.
Fullerenes	Hollow spherical structures	Unique chemical reactivity and energetic scheme; large value of the electron affinity energy, potential applications in drug delivery and nanomedicine.

Table 1. (*Continued*).

Type of nanocarbon	**Structure**	**Properties and applications**
Carbon nanodots	Small carbon nanoparticles with quantum effects	Fluorescence properties; used in bioimaging, sensors, and drug delivery.
Carbon nanofibers (CNFs)	Fibrous structures	High mechanical strength, used in composites, batteries, and sensors.
Activated carbon	Highly porous structure	High adsorption capacity; used in water purification, air filtration, and energy storage.
Carbon quantum dots	Small carbon nanoparticles with quantum effects	Unique optical properties; used in bioimaging, sensors, and solar cells.

Nanocarbons have gained significant attention in various fields, including nanotechnology, materials science, electronics, and medicine, due to their unique properties and potential for innovative applications. Researchers continue to explore ways to harness the properties of nanocarbons for developing advanced materials and technologies. **Figure 1** highlights the versatility and wide-ranging potential of nanocarbons across different industries and sectors.

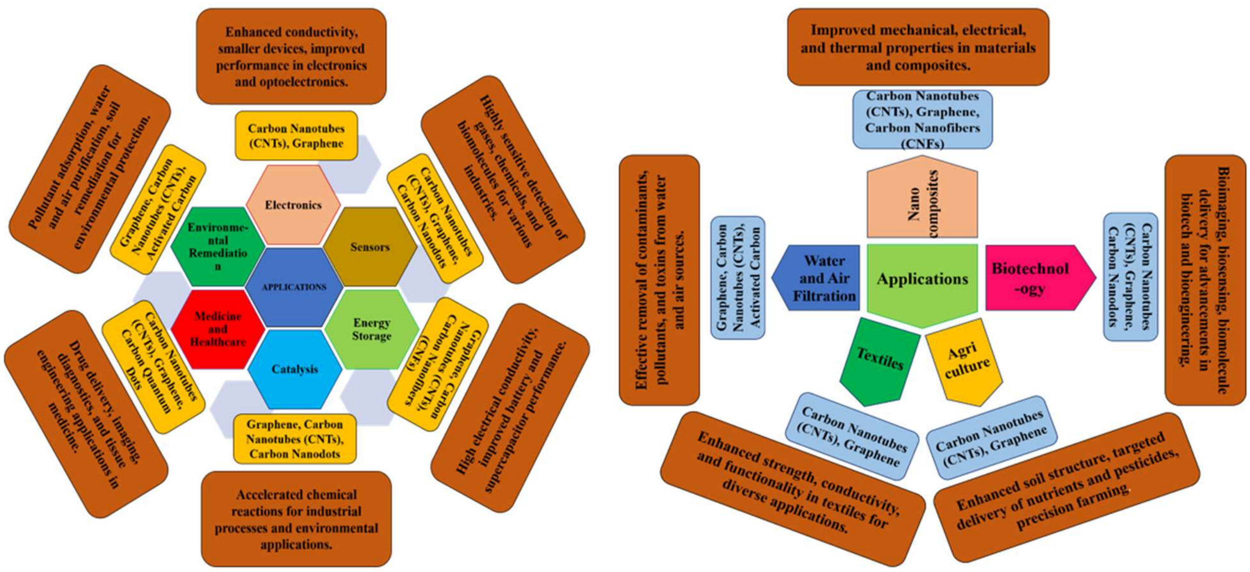

Figure 1. Applications of nanocarbon.

Nanocarbon, a term used to describe nanomaterials made of carbon, shows potential in domains including agriculture. **Table 2** demonstrates the potential of nanocarbon materials to improve various aspects of agriculture, from enhancing crop growth and protection to optimizing resource utilization and sustainability in farming practices. The distinct characteristics of nanocarbon materials make them well-suited for uses such as boosting crop yields, enhancing soil quality, and mitigating environmental effects. Nanocarbon materials, such as carbon nanotubes and graphene, can be incorporated into the soil to enhance its physical and chemical properties. These materials can improve water retention, nutrient holding capacity, and cation exchange capacity, leading to better soil fertility and plant growth[1]. Nanocarbons can serve as carriers for fertilizers and agrochemicals. By attaching nutrients or pesticides to nanocarbon surfaces, targeted and controlled release of these substances can be achieved, reducing excessive application and minimizing environmental pollution. The slow and controlled release of nutrients also ensures their efficient utilization by plants[2]. Certain nanocarbon materials have shown the ability to act as plant growth promoters when applied in small quantities. They can stimulate plant root development, increase nutrient uptake, and boost overall growth and yield[3]. Nanocarbon-based formulations can be used to develop nanopesticides, which have shown potential for providing effective and targeted pest control. These formulations can improve the efficiency of pest management while reducing the amount of pesticide required[4].

Table 2. Applications of nanocarbon in agriculture.

Application area	Nanocarbon application	Benefits and impacts
Soil improvement	Nanocarbon soil additives	Improved soil structure and nutrient retention
	Nanocarbon-based soil amendments	Enhanced microbial activity and fertility
Nutrient management	Nanocarbon-coated fertilizers	Controlled nutrient release and efficiency
	Nanocarbon nutrient carriers	Better nutrient uptake and reduced leaching
Pest control	Nanocarbon-based pesticides	Targeted pest control and reduced pollution
	Nanocarbon-enhanced biopesticides	Reduced environmental impact
Water purification	Nanocarbon-based water filters	Contaminant removal and improved water quality
	Nanocarbon for heavy metal adsorption	Cleaning polluted water sources
Crop monitoring	Nanocarbon-enabled sensors	Real-time data for optimized cultivation
	Nanocarbon-enhanced imaging systems	Detailed insights into crop health and growth
Environmental remediation	Nanocarbon-based soil remediation	Contaminant adsorption and soil restoration
	Nanocarbon for air and water clean-up	Removal of pollutants and toxins
Smart delivery systems	Nanocarbon-controlled release systems	Targeted and controlled delivery of substances
	Nanocarbon-responsive sensors	Environment-triggered payload release
Precision agriculture	Nanocarbon-enabled precision farming	Tailored practices for optimized yields
	Nanocarbon-based data-driven decisions	Enhanced resource efficiency
Customized plant nutrition	Nanocarbon nutrient release systems	Customized nutrient delivery for plants
	Nanocarbon-modified soil amendments	Improved nutrient availability and plant growth
Smart pest management	Nanocarbon-based pest control systems	Reduced chemical usage and environmental impact
	Nanocarbon-enabled precision pest control	Targeted and timely interventions

Nanocarbon can be used in water purification and nutrient delivery systems. For instance, carbon nanotubes can act as filters to remove contaminants and pollutants from water, making it suitable for irrigation. Additionally, nanocarbon-based nanosensors can monitor soil nutrient levels and enable precise and optimized nutrient application[5]. Nanocarbon coatings on seeds can enhance their germination rates, early-stage growth, and resistance to stress conditions. These coatings can also protect seeds from pests and diseases, leading to improved crop establishment[6]. Nanocarbon-based delivery systems can precisely deliver growth-promoting substances, fertilizers, or biopesticides to specific plant tissues or cells, resulting in improved efficacy and reduced wastage. Nanocarbon materials, particularly carbon nanotubes, have shown potential in environmental remediation applications. They can be used to remove pollutants and heavy metals from contaminated soils, thus restoring soil health[7]. Nanosensors based on nanocarbon can be used for real-time monitoring of various crop parameters, such as soil moisture, nutrient levels, and pest presence. This data can be used to implement precision agriculture practices and optimize resource usage[8]. However, it's important to note that the application of nanocarbon in agriculture is still a developing field, and more research is needed to fully understand the long-term impacts on both plants and the environment. Safety and regulatory considerations are also crucial when introducing nanocarbon-based products into agricultural systems to ensure they pose no harm to humans, animals, or the ecosystem.

2. Soil amendment and fertility improvement

Nanocarbon materials, such as carbon nanotubes (CNTs), graphene, and carbon nanoparticles, have shown great potential for various applications due to their unique physical, chemical, and mechanical properties. One promising area where nanocarbon materials can be applied is in soil amendment and fertility improvement. However, it's important to note that while nanocarbon materials hold promise, their environmental impact and long-term effects on soil ecosystems require thorough research and consideration. Regulatory aspects, potential toxicity, and scalability of production also need to be carefully evaluated before widespread implementation. Here's a detailed application of nanocarbon in this context:

2.1. Enhancement of soil structure, nutrient retention, and slow release

Nanocarbon materials can be added to soil to improve its physical properties. Due to their nanoscale dimensions and high surface area, they can act as structural reinforcements, enhancing soil aggregation and stability[9]. This helps prevent soil erosion and compaction, which are common issues leading to decreased soil fertility. Nanocarbon materials can adsorb and retain nutrients, preventing them from leaching away due to rainfall or excessive irrigation. Additionally, these materials can act as carriers for slow nutrient release[10]. This controlled nutrient release ensures that plants have a steady supply of essential elements over time, reducing the need for frequent fertilization.

2.2. pH regulation and microbial habitat improvement

Some nanocarbon materials have surface functional groups that can influence soil pH. By incorporating these materials into the soil, it's possible to regulate pH levels in acidic or alkaline soils, creating a more favorable environment for plant growth and nutrient availability[11]. Nanocarbon materials can create a conducive environment for beneficial soil microorganisms. Their high surface area provides ample space for microbial attachment and growth[12]. Enhanced microbial activity can lead to improved nutrient cycling, organic matter decomposition, and overall soil health.

2.3. Enhanced water holding capacity

Nanocarbon materials can improve soil's water-holding capacity by increasing its porosity and water retention. This is especially important in arid and semi-arid regions where water availability is limited. Improved water retention reduces irrigation frequency and enhances plant survival[13].

2.4. Remediation of contaminated soils and carbon sequestration

Nanocarbon materials have the ability to adsorb various pollutants and contaminants from the soil, including heavy metals and organic pollutants[14]. Adding these materials to contaminated soils can facilitate the remediation process by reducing the bioavailability of harmful substances. Using nanocarbon materials in soil can contribute to carbon sequestration, helping to mitigate climate change[11]. These materials are rich in carbon and can persist in the soil for extended periods. By incorporating nanocarbon, carbon can be effectively stored in the soil and prevented from entering the atmosphere as carbon dioxide.

2.5. Plant growth promotion

Certain nanocarbon materials have been shown to stimulate plant growth by enhancing nutrient uptake, root development, and overall physiological processes. They can also act as elicitors, triggering plant defense mechanisms and increasing resistance to biotic and abiotic stressors[15].

2.6. Reduced pesticide dependency and long-term soil health

When nanocarbon materials are applied to soil, they can enhance the efficacy of pest and disease management[16]. By creating a microenvironment that supports beneficial microorganisms, plants are better protected against harmful pathogens, potentially reducing the need for chemical pesticides. Overall, the incorporation of nanocarbon materials can contribute to long-term soil health and fertility. By addressing soil structure, nutrient availability, water retention, and microbial activity, these materials offer a holistic approach to improving soil quality and promoting sustainable agriculture.

3. Nano-fertilizers

Nanocarbon materials can be used as nano-fertilizers to enhance nutrient delivery, improve plant growth, and increase crop yields. Nano-fertilizers offer several advantages over traditional fertilizers, including improved nutrient efficiency, controlled release, and targeted delivery. Despite the potential benefits, the application of nanocarbon as nano-fertilizers also poses challenges. Issues such as potential toxicity, long-term environmental impacts, and regulatory considerations need to be thoroughly studied and addressed before widespread adoption. Research must focus on optimizing formulations, understanding plant interactions, and ensuring the safe use of nanocarbon-based products in agriculture. Here's a detailed application of nanocarbon as nano-fertilizers:

3.1. Nutrient encapsulation, controlled release, and increased nutrient uptake

Nanocarbon materials can encapsulate nutrients like nitrogen, phosphorus, and potassium within their structures. This encapsulation allows for the controlled release of nutrients over time, reducing nutrient leaching and ensuring a steady supply of nutrients to plants[17]. This controlled release matches the nutrient requirements of the plants during different growth stages. Nanocarbon materials can enhance the uptake of nutrients by plants due to their high surface area and ability to interact with root surfaces[18]. This leads to improved nutrient availability for plant roots, resulting in better growth and development.

3.2. Enhanced soil retention, stability, and micronutrient delivery

When nanocarbon-based nano-fertilizers are applied to soil, they can improve soil structure and stability, reducing nutrient runoff and erosion[19]. This helps retain nutrients within the root zone, making them more accessible to plants. Nanocarbon materials can be functionalized with specific molecules to carry micronutrients like iron, zinc, and copper[1]. These micronutrients are essential for various metabolic processes in plants. Nano-fertilizers can enhance the availability and uptake of micronutrients, addressing deficiency-related issues.

3.3. pH and soil interaction management

Functionalized nanocarbon materials can be engineered to interact with soil pH, enhancing nutrient solubility and availability in soils with varying pH levels. This ensures that plants receive the required nutrients even in soils with pH-related limitations[1].

3.4. Targeted delivery and stress tolerance

Nano-fertilizers can be designed to target specific plant tissues or root zones, reducing waste and improving nutrient utilization. This targeted delivery minimizes environmental impacts and optimizes nutrient efficiency. Nanocarbon-based nano-fertilizers can improve a plant's tolerance to drought and various stresses[20]. They can stimulate the production of stress-related proteins and antioxidants, helping plants cope with adverse conditions.

3.5. Environmental impact reduction and sustainable agriculture

Nano-fertilizers can mitigate the negative environmental effects associated with excessive fertilizer application. Their controlled release mechanisms and improved nutrient uptake reduce the risk of nutrient runoff into water bodies, which can cause water pollution and eutrophication. By optimizing nutrient delivery and reducing the need for frequent fertilizer application, nano-fertilizers contribute to sustainable agricultural practices. They help increase crop yields while minimizing resource consumption and environmental impact.

3.6. Compatibility with other agricultural inputs

Nanocarbon-based nano-fertilizers can be used in conjunction with other agricultural inputs, such as pesticides and growth regulators. Their compatibility ensures that plants receive comprehensive treatment to enhance overall health and productivity.

4. Plant growth promoters

Nanocarbon can enhance various aspects of plant growth and development, leading to increased yields and improved crop quality. It's important to note that the application of nanocarbon as a plant growth promoter is an emerging field with ongoing research[21]. While the potential benefits are significant, factors like dosage, application methods, long-term effects, and potential environmental impacts require careful consideration. Regulatory aspects and safety concerns also need to be addressed before large-scale implementation in agriculture[22]. Here's a detailed application of nanocarbon as a plant growth promoter:

4.1. Seed germination and early growth

Nanocarbon materials can be applied to seeds or seedlings to enhance germination rates and early growth. The high surface area of these materials can help retain moisture around seeds, providing a conducive environment for germination. Additionally, nanocarbon can stimulate enzyme activity and nutrient absorption, promoting healthy seedling establishment.

4.2. Root growth, development, and enhanced photosynthesis

Nanocarbon materials can stimulate root growth by providing a physical structure that supports root elongation and branching. They can also secrete root-growth-promoting compounds due to their unique chemical properties, leading to a well-developed root system that improves overall plant health and nutrient uptake. Nanocarbon materials can improve photosynthetic efficiency by enhancing the absorption of light and facilitating electron transfer processes in chloroplasts. This leads to increased production of carbohydrates and energy, supporting plant growth and productivity.

4.3. Stress tolerance and disease resistance

Nanocarbon-based plant growth promoters can enhance a plant's tolerance to various environmental stresses, such as drought, salinity, and temperature fluctuations. They can trigger the expression of stress-responsive genes and activate antioxidant systems, reducing the negative impact of stress on plant health. Nanocarbon-based growth promoters can enhance a plant's resistance to pathogens by inducing the synthesis of defense-related compounds. This can improve the plant's ability to fend off diseases and reduce the need for chemical pesticides.

4.4. Hormone regulation, flowering, and fruit development

Nanocarbon materials can influence plant hormone levels and signaling pathways. They can act as hormone mimics or regulators, promoting processes such as cell division, elongation, and differentiation, which are essential for plant growth and development. Nanocarbon materials can influence flowering and fruiting processes by regulating hormonal balances and promoting nutrient transport. This can lead to increased flower production, better pollination, and improved fruit quality.

4.5. Longevity and senescence delay

Nanocarbon-based growth promoters can delay senescence (aging) in plants by maintaining chlorophyll content and delaying the breakdown of cell membranes. This can extend the productive lifespan of plants and increase the duration of photosynthetic activity.

4.6 Sustainable agriculture and controlled release of bioactive compounds

Using nanocarbon materials as plant growth promoters aligns with sustainable agricultural practices. They can reduce the need for excessive fertilizer and pesticide application while increasing crop yields and resource use efficiency. Functionalized nanocarbon materials can be loaded with specific bioactive compounds, such as growth regulators, nutrients, or beneficial microorganisms. These materials can then release these compounds gradually, providing long-lasting effects on plant growth and health.

5. Crop protection

The application of nanocarbon materials for crop protection involves utilizing their unique properties to develop innovative strategies for mitigating pest and disease pressures in agriculture. Nanocarbon-based crop protection approaches can offer targeted and sustainable solutions that minimize environmental impact and reduce the reliance on conventional chemical pesticides[4,23]. While nanocarbon-based crop protection holds promise, challenges remain, including regulatory approval, potential toxicity to non-target organisms, and long-term environmental impacts. Comprehensive risk assessments, as well as thorough research on efficacy and safety, are necessary before the widespread adoption of nanocarbon-based crop protection methods. Here’s a detailed application of nanocarbon as crop protection:

5.1. Nanoparticle-based pesticides with enhanced delivery

Nanocarbon materials can be functionalized with specific compounds that have pesticidal properties. These nanoparticles can be designed to target specific pests while sparing beneficial insects and non-target organisms. Functionalized nanocarbon particles can disrupt pest physiology, interfere with their growth and development, or disrupt their reproductive processes. Nanocarbon materials can act as carriers for traditional pesticides, ensuring their controlled and targeted release. These carriers can protect the pesticides from degradation and leaching, reducing the need for frequent applications. This approach improves pesticide efficiency and minimizes environmental contamination.

5.2. Disease management

Functionalized nanocarbon materials can be used to deliver antimicrobial agents or elicitors that trigger plant defense mechanisms against diseases. These materials can inhibit the growth of pathogens, boost the plant’s immune response, and reduce the need for chemical fungicides.

5.3. Nanocarbon-encapsulated biopesticides and smart release systems

Biopesticides, such as beneficial microorganisms or plant extracts, can be encapsulated within nanocarbon materials. This encapsulation protects the biopesticides from environmental conditions, improves their stability, and enhances their adherence to plant surfaces. Nanocarbon materials can be engineered to release pesticides in response to specific environmental cues, such as temperature, humidity, or pest presence. This "smart" release system ensures that pesticides are deployed only when needed, minimizing non-target exposure.

5.4. Nanocarbon-mediated RNA interference (RNAi)

Nanocarbon-based delivery systems can be used to introduce double-stranded RNA molecules into pests. These molecules can silence target genes and disrupt pest development, offering a highly specific and environmentally friendly approach to pest control.

5.5. Reduced pesticide resistance and weed management

Nanocarbon-based approaches can help reduce the development of pesticide-resistant pest populations. By utilizing unique modes of action or targeting essential biological processes, these materials can overcome the mechanisms that lead to pesticide resistance. Nanocarbon materials can also be used to develop targeted weed management solutions. Nanocarbon-based herbicides can be designed to selectively target and inhibit weed growth without affecting crops.

5.6. Controlled barrier films and reduced environmental impact

Nanocarbon-based films can be applied to plants as protective barriers against pests. These films can physically block pest access, create unfavorable conditions for pest attachment, or release repellent compounds, reducing pest damage. Nanocarbon-based crop protection strategies often have a lower environmental impact compared to conventional chemical pesticides. Their targeted application minimizes non-target effects and reduces chemical residues in the environment.

6. Water and nutrient management

Nanocarbon materials have the potential to revolutionize water and nutrient management in agriculture by improving water retention, nutrient delivery, and overall resource use efficiency. These materials can address challenges related to water scarcity, nutrient loss, and environmental impact[24]. It's important to note that while nanocarbon-based solutions hold promise, careful research is needed to assess their long-term effects on soil health, plant growth, and potential environmental risks. Regulatory considerations, scalability of production, and cost-effectiveness also need to be evaluated before widespread adoption in agricultural systems. Here's a detailed application of nanocarbon in water and nutrient management:

6.1. Water retention, irrigation efficiency, and controlled nutrient release

Nanocarbon materials can be added to soil to improve water retention. Their high surface area and porous structure can hold water molecules through capillary forces, reducing the frequency of irrigation. This is particularly beneficial in arid and drought-prone regions where water availability is limited. Nanocarbon materials can encapsulate nutrients, such as nitrogen, phosphorus, and potassium, and release them gradually based on soil moisture conditions. This controlled release matches nutrient availability to plant demand, reducing nutrient leaching and enhancing uptake efficiency.

6.2. Nutrient uptake enhancement, chelation, and solubility

The unique properties of nanocarbon materials can improve nutrient uptake by plants. They can increase the surface area of roots, facilitating better contact with nutrients in the soil. Nanocarbon can also enhance root exudation, promoting the release of compounds that attract beneficial microorganisms that assist in nutrient uptake. Nanocarbon materials can be functionalized to chelate or complex nutrients, making them more available to plants. This can enhance the solubility of otherwise poorly soluble nutrients, ensuring their efficient uptake by plant roots.

6.3. pH regulation, nutrient availability, and water purification

Functionalized nanocarbon materials can influence soil pH and nutrient availability. They can release ions that modify the pH, making certain nutrients more accessible to plants. This is particularly useful in soils with pH-related nutrient deficiencies. Nanocarbon materials can be used in water filtration systems to remove contaminants, pollutants, and heavy metals from irrigation water. Their porous structure and adsorption properties make them effective adsorbents for water purification.

6.4. Desalination, monitoring, and sensor systems

Nanocarbon-based membranes and filters can be used for desalination, removing excess salts from water sources. This is crucial for agriculture in areas with high salinity levels, where soil and water quality can negatively impact crop growth. Nanocarbon materials can be integrated into sensors to monitor soil moisture, nutrient levels, and environmental conditions in real time. This data can be used to optimize irrigation and nutrient application, reducing waste and enhancing resource efficiency.

6.5. Reduced environmental impact and improved crop productivity

The use of nanocarbon materials for water and nutrient management can reduce the environmental impact associated with excessive fertilizer and water use. This contributes to more sustainable agricultural practices and mitigates water pollution and nutrient runoff. Overall, the incorporation of nanocarbon materials in water and nutrient management practices can lead to improved crop productivity. By optimizing water availability and nutrient supply, plants can achieve their growth potential while minimizing resource inputs.

7. Seed coatings

Nanocarbon-based seed coatings offer innovative solutions to improve seed quality, germination rates, and early plant growth. These coatings can provide a protective barrier, enhance nutrient uptake, and deliver bioactive compounds to seeds, contributing to more resilient and productive crops[25]. However, the adoption of nanocarbon-based seed coatings requires careful consideration of factors such as toxicity, compatibility with different seed types, regulatory approvals, and cost-effectiveness. Rigorous testing and research are necessary to ensure that the coatings provide the desired benefits without causing unintended harm to the environment or human health. Here’s a detailed application of nanocarbon as seed coatings:

7.1. Protection from environmental stress and enhanced water absorption and retention

Nanocarbon coatings can form a protective shield around seeds, safeguarding them from adverse environmental conditions such as temperature fluctuations, UV radiation, and moisture stress. This protection promotes higher germination rates and ensures seed viability. Nanocarbon coatings can improve the water-absorbing capacity of seeds, enhancing the speed and uniformity of germination. The high surface area and porosity of nanocarbon materials contribute to better water retention around the seed, maintaining the necessary moisture for germination.

7.2. Beneficial microorganism delivery and controlled release of nutrients

Nanocarbon-coated seeds can carry beneficial microorganisms such as mycorrhizal fungi or nitrogen-fixing bacteria. These microorganisms enhance nutrient uptake and plant growth, creating a symbiotic relationship that supports crop development. Nanocarbon coatings can encapsulate essential nutrients or fertilizers, releasing them gradually as the seed germinates. This provides a nutrient source during the critical early growth stages, promoting healthy seedling development.

7.3. Germination timing, synchronization, and sustainable agriculture

Nanocarbon coatings can be engineered to respond to specific environmental cues, triggering germination in the most favorable conditions. This can help synchronize germination within a planting area, improving crop uniformity. Nanocarbon-based seed coatings contribute to sustainable agriculture by reducing the need for excessive water and chemical inputs. They enhance seed performance, leading to higher yields and resource efficiency.

7.4. Disease resistance, pest management, and stress tolerance enhancement

Nanocarbon coatings can include antimicrobial agents or pest-repelling compounds that protect seeds from soilborne pathogens and pests. This early protection minimizes the need for chemical treatments later in the crop cycle. Nanocarbon-coated seeds can be designed to carry stress-responsive molecules that help plants tolerate environmental stresses like drought, salinity, or temperature fluctuations during early growth stages.

7.5. Improved seed adhesion, planting, and bioactive compound delivery

Nanocarbon coatings can enhance seed adhesion during planting, ensuring better seed-to-soil contact. This improves the likelihood of successful germination and establishment, especially in challenging soil conditions. Nanocarbon coatings can deliver bioactive compounds like growth promoters, hormones, or disease resistance inducers directly to seeds. This ensures that plants receive the necessary signals for optimal growth and development from the very beginning.

8. Smart delivery systems

Nanocarbon-based smart delivery systems utilize the unique properties of nanocarbon materials to deliver various substances, such as drugs, nutrients, or pesticides, in a controlled and targeted manner. These systems respond to specific environmental cues or stimuli to release their payloads, improving efficiency, reducing waste, and minimizing adverse effects[26,27]. While nanocarbon-based smart delivery systems hold promise, challenges like precise control of release, potential toxicity, and regulatory approval need to be addressed. Rigorous testing, characterization, and optimization are necessary to ensure the systems function as intended and are safe for both human health and the environment. Here's a detailed application of nanocarbon as a smart delivery system:

8.1. Environmental sensing

Nanocarbon materials can be engineered to detect specific environmental cues, such as pH, temperature, humidity, or the presence of certain molecules. These cues act as triggers for the release of the encapsulated payload, ensuring delivery at the right time and place.

8.2. pH, temperature, and light-responsive systems

Nanocarbon-based systems can respond to changes in pH levels. For example, they can remain stable in the stomach's acidic environment and release their payload at the more neutral pH of the intestines. In agriculture, these systems can release nutrients or pesticides in response to soil pH. Nanocarbon materials can be designed to release their payload when exposed to specific temperature ranges. This is particularly useful in applications like drug delivery, where localized hyperthermia can trigger drug release at the site of a tumor. Certain nanocarbon materials are sensitive to light at specific wavelengths. They can absorb light energy and convert it into heat, which triggers the release of the payload. This mechanism can be exploited in medical treatments or for targeted pesticide release in agriculture.

8.3. Stimuli-responsive drug delivery and disease diagnosis and treatment

Nanocarbon-based smart delivery systems can carry drugs or therapeutic agents and release them in response to specific physiological conditions, such as inflammation, infection, or cellular stress. This enhances the efficiency of drug delivery while minimizing side effects. Nanocarbon-based systems can be designed to target specific disease markers and release diagnostic agents or therapeutic compounds in response to their detection. This is particularly relevant in the field of medicine for early disease detection and treatment.

8.4. Nutrient release for plants and controlled release of pesticides

Nanocarbon-based systems can be used to encapsulate and deliver nutrients to plants in response to their growth stages. For example, the system could release nutrients gradually during critical growth phases, matching the plant's nutritional demands. In agriculture, nanocarbon-based smart systems can be employed to release pesticides in response to pest presence or other cues. This targeted release reduces the need for frequent pesticide applications, minimizing environmental impact.

8.5. Waste reduction and efficiency improvement

Smart delivery systems minimize wastage by releasing payloads only when required, improving efficiency and reducing overexposure. This is especially important in pharmaceuticals and agriculture, where excess use of drugs or chemicals can have negative consequences.

8.6. Personalized medicine and agriculture

Nanocarbon-based smart delivery systems can be tailored to individual needs, enabling personalized treatments for patients or crops. This precision reduces the likelihood of adverse effects and enhances the effectiveness of interventions.

9. Environmental remediation

Nanocarbon materials have shown significant potential for environmental remediation due to their unique properties, such as high surface area, reactivity, and adsorption capacity[28]. They can be used to remove pollutants, contaminants, and toxins from air, water, and soil, contributing to cleaner and healthier ecosystems[29,30]. While nanocarbon-based environmental remediation holds promise, challenges include scalability, cost-effectiveness, potential long-term effects, and ensuring that the materials themselves do not become pollutants. Comprehensive research, testing, and regulatory considerations are essential to ensuring the safety and effectiveness of these approaches in addressing environmental pollution. Here's a detailed application of nanocarbon in environmental remediation:

9.1. Water and soil remediation

Nanocarbon materials can be used to remove pollutants from water sources. They can adsorb heavy metals, organic compounds, and even microorganisms, effectively purifying water for drinking, industrial use, or ecosystem restoration. Nanocarbon-based systems can be applied to contaminated soils to adsorb, sequester, or transform pollutants. They can bind with heavy metals, organic pollutants, and radioactive elements, reducing their mobility and bioavailability. Nanocarbon materials can be used to treat groundwater contaminated with organic compounds, pesticides, or industrial chemicals. They can adsorb these contaminants, effectively purifying the groundwater before it enters natural water bodies.

9.2. Air quality improvement

Nanocarbon materials can capture airborne pollutants, including volatile organic compounds (VOCs), particulate matter, and gases like nitrogen dioxide. These materials can be integrated into air filters, masks, or catalytic converters to improve indoor and outdoor air quality.

9.3. Oil spill clean-up

Nanocarbon materials can adsorb hydrophobic substances like oil and hydrocarbons from water surfaces. Their high adsorption capacity makes them effective tools for cleaning up oil spills and preventing environmental damage.

9.4. Electrochemical remediation

Nanocarbon-based electrodes can be employed in electrochemical methods for remediation. They can oxidize or reduce pollutants, breaking them down into less harmful substances. This technique is effective for treating wastewater or contaminated groundwater.

9.5. Radioactive waste cleanup and emerging contaminant removal

Nanocarbon materials can bind with radioactive ions, contributing to the cleanup of nuclear waste sites. They can immobilize radioactive elements and reduce their leaching into the environment. Nanocarbon materials are being explored for the removal of emerging contaminants, such as pharmaceutical residues and microplastics, from water and soil. Their adsorption capabilities make them potential solutions for addressing these new challenges.

9.6. Carbon capture storage (CCS) and ecosystem restoration

Nanocarbon materials can capture carbon dioxide (CO_2) from industrial flue gases, contributing to carbon capture and storage efforts to mitigate climate change. Their high surface area facilitates CO_2 adsorption. By removing pollutants and contaminants, nanocarbon-based remediation techniques can help restore ecosystems that have been impacted by pollution. This promotes biodiversity and ecological health.

10. Improved crop monitoring

Nanocarbon materials can revolutionize crop monitoring by enhancing the accuracy, efficiency, and precision of data collection[31]. They can be integrated into various monitoring systems to provide real-time insights into crop health, growth, and environmental conditions[32]. It's important to note that while nanocarbon-based crop monitoring offers numerous benefits, challenges include sensor calibration, data accuracy validation, and potential cost considerations. Ensuring the reliability and safety of these monitoring systems is essential to their successful adoption in agriculture. Here's a detailed application of nanocarbon in improved crop monitoring:

10.1. Nanocarbon-based sensors

Nanocarbon materials can be used to create sensors that monitor various environmental parameters such as soil moisture, temperature, humidity, pH, and nutrient levels. These sensors provide accurate and continuous data, enabling farmers to make informed decisions about irrigation, fertilization, and other cultivation practices.

10.2. Wireless sensor networks

Nanocarbon-based sensors can be connected wirelessly to form networks that cover larger agricultural areas. These networks collect and transmit data to a central system, providing a comprehensive view of crop conditions and environmental trends.

10.3. Nanocarbon-enhanced imaging and early disease detection

Nanocarbon materials can be integrated into imaging systems, such as drones or satellites, to capture high-resolution images of crops. These images can reveal detailed information about plant health, growth patterns, and stress indicators. Nanocarbon-based sensors can detect early signs of disease or pest infestations by monitoring changes in plant physiology, such as altered metabolic activity or stress responses. This enables timely interventions to prevent the spread of diseases.

10.4. Nutrient monitoring, optimization, and real-time environmental monitoring

Nanocarbon sensors can monitor nutrient levels in the soil and plant tissues, allowing farmers to adjust fertilizer applications based on actual plant requirements. This minimizes nutrient waste and reduces environmental pollution. Nanocarbon-based sensors can track factors like light intensity, CO_2 levels, and air quality within the growing environment. This data helps optimize growth conditions in controlled environments like greenhouses.

10.5. Data-driven irrigation management, remote monitoring, and automation

Nanocarbon sensors that measure soil moisture and weather conditions can guide precision irrigation practices. This reduces water waste and ensures that plants receive the optimal amount of water. Nanocarbon-enabled monitoring systems can be accessed remotely through smartphones or computers. This enables farmers to monitor and manage their crops from anywhere, enhancing operational efficiency.

10.6. Precision harvesting and sustainable practices

Nanocarbon-enhanced imaging and sensor data can guide precision harvesting by identifying the optimal time for harvest based on factors like crop maturity and yield potential. Nanocarbon-based crop monitoring data can be integrated into decision support systems that offer recommendations and insights for farm management. These systems combine data from various sources to provide actionable information. Improved crop monitoring with nanocarbon technology helps farmers adopt more sustainable practices by reducing resource waste, optimizing inputs, and minimizing the use of chemicals.

11. Conclusions and future perspective

In conclusion, the application of nanocarbon materials in agriculture holds substantial promise for addressing various challenges and advancing sustainable farming practices. Nanocarbon's exceptional properties, including high surface area, reactivity, and versatility, enable innovative solutions across different aspects of agriculture. Nanocarbon offers multifaceted benefits, from soil improvement and nutrient management to pest control, water purification, and crop monitoring. Nanocarbon's ability to improve soil structure, nutrient retention, and water availability directly contributes to increased crop yields and improved quality. Controlled nutrient release, improved water retention, and precise pest management reduce the excessive use of fertilizers, water, and pesticides, promoting efficient resource utilization. Nanocarbon-based solutions minimize the environmental impact of agriculture by reducing pollution, nutrient runoff, and chemical usage, thereby promoting ecological balance. Nanocarbon-enabled sensors and monitoring systems provide real-time insights, enabling farmers to make informed decisions for optimized cultivation, irrigation, and pest management. Nanocarbon's role in enhancing stress tolerance and disease resistance empowers plants to withstand environmental pressures, contributing to more resilient crops. In water and soil remediation, nanocarbon's adsorption capabilities offer efficient removal of pollutants and contaminants, leading to cleaner ecosystems. Precision delivery of nutrients, pesticides, and bioactive compounds minimizes human and environmental exposure to potentially harmful substances. Rigorous research into nanocarbon's long-term effects, potential toxicity, and scalability is crucial to ensuring its safe and sustainable integration into agricultural practices. Collaboration among researchers, regulators, and farmers is essential to navigate these challenges and maximize the benefits of nanocarbon in agriculture. Overall, nanocarbon materials offer a pathway to more efficient, environmentally friendly, and productive agriculture, contributing to global food security and sustainable resource management.

The future of nanocarbon applications in agriculture is promising, with ongoing research and technological advancements poised to revolutionize various aspects of farming. Nanocarbon-based sensors and monitoring systems will enable real-time data collection on plant health, soil conditions, and environmental factors. This will drive the shift towards precision agriculture, allowing farmers to tailor their practices with unparalleled accuracy, leading to optimized yields and reduced resource waste. Advanced nanocarbon formulations will offer precise nutrient delivery based on plant requirements, growth stages, and soil conditions. Tailored nutrient management will not only increase crop productivity but also minimize nutrient runoff and environmental pollution. The development of nanocarbon-based smart delivery systems for pesticides will enable targeted pest control. These systems can release pesticides only in the presence of specific pests, reducing chemical usage and the impact on non-target organisms. Nanocarbon materials may facilitate gene delivery for plant genetic modification. They could also help in developing stress-tolerant and disease-resistant crop varieties through the precise delivery of genetic material. Nanocarbon-enhanced fertilizers will play a pivotal role in addressing nutrient deficiencies and improving soil health. These nanofertilizers could be designed to release nutrients according to crop demand, reducing excess fertilizer application. Nanoagrochemicals will emerge as safer and more efficient alternatives to conventional agrochemicals. Nanocarbon can enhance the stability, solubility, and targeted delivery of these compounds, reducing their environmental impact. Greenhouse and indoor farming will benefit from nanocarbon materials that enhance light absorption, heat distribution, and moisture retention, creating optimal growth conditions for crops. Advanced nanocarbon-based materials will offer effective solutions for remediating contaminated soils. Their ability to adsorb heavy metals and organic pollutants will contribute to land restoration. Nanocarbon-based packaging materials could extend the shelf life of agricultural products and reduce post-harvest losses. These materials could also be used to develop sustainable crop protection methods. As the use of nanocarbon in agriculture grows, regulations will evolve to ensure safety for both the environment and human health. Continued research into the potential toxicity and environmental impact of nanocarbon materials will be crucial. In the coming years, collaborative efforts between scientists, engineers, farmers, and policymakers will be essential to harnessing the full potential of nanocarbon in agriculture. This interdisciplinary approach will drive innovation, promote sustainability, and address the challenges faced by modern agriculture.

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Conflict of interest

The author declares no conflict of interest.

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