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Biorefining agro-industrial waste into green nano-material for sustainable agriculture – A review

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Abstract

Biorefining is a process that involves the conversion of biomass (organic materials) into various products such as biofuels, chemicals, and materials. Agro-industrial waste, which is usually considered a problem due to its disposal challenges, can be converted into valuable green nanomaterials through a biorefining process. This chapter explains about neumorous nanomaterials and respective applications in sustainable agriculture such as Nanofertilizers, Nanopesticides, Nanomulches, Nanomaterial-based Sensors, Nanomaterials for Soil Remediation, Nanoparticles for Seed Coatings etc. The concept of repurposing agro-industrial waste into green nanomaterials aligns with the principles of sustainability by reducing waste and promoting resource efficiency. This approach reduces the amount of agro-industrial waste in landfills, minimizes the need for chemical inputs, and promotes sustainable agricultural practices. It can help reduce the carbon footprint of agriculture and minimize environmental pollution. Sustainable agriculture practices can also have economic and social benefits by promoting local economies, reducing production costs, and ensuring a more stable food supply. However, it's important to ensure that the use of nanomaterials in agriculture is safe for both the environment and human health. This chapter represents state-of-the-art innovations to transform Agro-industrial waste into sustainable agriculture products and bioeconomy.

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Introduction

Crop improvement is a critical area of research and practice in agriculture, aimed at enhancing the quality, yield, disease resistance, and adaptability of crops to various environmental stresses. The primary goal is to meet the growing demand for food, feed, and fiber while addressing challenges like climate change, soil degradation, water scarcity, and pest resistance (Squire et al., 2023).

NPs for development of Efficient gene transformation Vehicles

Nanoparticles (NPs) have shown great promise in the development of efficient gene transformation vehicles due to their unique properties, such as small size, high surface area, biocompatibility, and the ability to be functionalized with a variety of molecules. These properties make nanoparticles an attractive option for delivering genetic material (such as DNA, RNA, or

CRISPR/Cas systems) into cells, a process essential for gene therapy, vaccine development, and other biotechnological applications (Hudson et al., 2019).

Nanomaterial based delivery of CRISPR/ Cas9 sgRNA

The nanomaterial-based delivery of CRISPR/Cas9 sgRNA (single guide RNA) is an emerging and promising strategy to enhance the efficiency and precision of genome editing. While CRISPR/Cas9 systems hold great potential for gene therapy, their successful application depends significantly on effective delivery mechanisms for the Cas9 protein and sgRNA into target cells. Nanomaterials, particularly nanoparticles (NPs), have garnered significant attention as delivery vehicles because of their ability to protect the CRISPR components, promote cellular uptake, and potentially offer targeted delivery to specific tissues or cell types. Lipid Nanoparticles (LNPs) are among the most studied carriers for CRISPR/Cas9 delivery (Demirer et al., 2021).

LNPs have a lipid bilayer that can encapsulate both sgRNA and Cas9 protein (or plasmids encoding them) and facilitate endocytosis and intracellular release. Polymeric nanoparticles such as those made from polyethylenimine (PEI), poly(lactic-co-glycolic acid) (PLGA), and chitosan can be used for CRISPR/Cas9 delivery. Gold nanoparticles (AuNPs) are widely used for gene delivery due to their high surface area, ease of functionalization, and biocompatibility. Carbon nanotubes (CNTs) and graphene oxide (GO) are increasingly studied for CRISPR/Cas9 delivery due to their high surface area, electrical conductivity, and ability to facilitate cellular internalization. Mesoporous silica nanoparticles are used to deliver both the Cas9 protein and sgRNA because of their large internal surface area, which can accommodate a significant amount of cargo. A critical aspect of CRISPR/Cas9 delivery is co-delivery of both the Cas9 protein and the sgRNA into the same cell. Nanoparticles are often used to deliver both components simultaneously, either as separate cargoes encapsulated within the same nanoparticle or within different particles, to ensure that the CRISPR system is functional inside the cell (Zhang et al., 2020). Nanoparticle-mediated delivery of CRISPR/Cas9 is still an active area of research, with ongoing efforts to improve the design of nanoparticles for enhanced targeting, cellular uptake, and gene editing efficiency.

Nano-transgenic plants

Nano-transgenic plants refer to genetically modified plants that are engineered with the aid of nanotechnology to enhance their traits, such as resistance to pests, diseases, environmental stresses, or to improve crop yield and nutritional content. Nanotechnology provides novel tools for the efficient delivery of genetic material, as well as the development of plant-based bio-sensors, fertilizers, pesticides, and other agrochemicals. The integration of nanomaterials into plant biotechnology holds great promise for sustainable agriculture by offering more targeted, efficient, and environmentally friendly solutions. CRISPR/Cas9 technology can be used to edit plant genes for improving traits like disease resistance, drought tolerance, pest resistance, and nutritional content. Nanoparticle-based delivery could make gene editing more precise and efficient in crops. Nanotechnology can also help in the delivery of RNA molecules (like siRNA or miRNA) that can regulate gene expression, enabling fine-tuned control of gene function in plants.

Nano-transgenic plants represent a cutting-edge approach to modern plant biotechnology, offering new opportunities to enhance crop productivity, resilience, and sustainability (Lv et al., 2020). By integrating nanomaterials with genetic engineering techniques like CRISPR/Cas9, researchers can develop more efficient, targeted, and environmentally friendly methods for crop improvement. However, further research is needed to optimize delivery systems, address safety concerns, and ensure the regulatory acceptance of these novel technologies.

Precision farming

Nano-sensor for monitoring soil condition

Nano-sensors for monitoring soil conditions are an emerging technology that leverages the unique properties of nanomaterials to provide real-time, accurate, and highly sensitive detection of various soil parameters. These sensors can significantly improve precision agriculture by allowing farmers to monitor and manage soil health, nutrient levels, moisture content, pH, and other important environmental factors that affect crop growth. The integration of nanotechnology in soil monitoring has the potential to revolutionize agricultural practices, enhancing crop productivity, minimizing resource waste, and ensuring sustainable farming (Bharti et al., 2024). Electrochemical nano-sensors are among the most common types used for detecting various soil parameters. These sensors typically operate by measuring the change in electrical properties (such as resistance, capacitance, or current) caused by the interaction of the target analyte with the sensor surface.

Optical sensors detect changes in light absorption, fluorescence, or scattering properties of nanomaterials when they interact with soil components. These sensors can provide real-time, non-invasive monitoring of soil conditions. SERS-based nano-sensors use the Raman scattering effect, which is enhanced by the presence of nanoparticles (such as gold or silver). These sensors are capable of detecting trace amounts of chemicals, making them ideal for monitoring contaminants and pollutants in soil. Magnetic nano-sensors are based on the properties of magnetic nanoparticles, which change their magnetic behavior in response to interactions with specific analytes. These sensors can be used to monitor various soil conditions, especially when detecting the presence of heavy metals or organic contaminants (Mandal et al., 2020). Nanowire sensors are made from semiconductor materials (like silicon, zinc oxide, or gold), and they can detect specific ions or molecules based on changes in the electrical conductance or resistance of the nanowires.

Nano-sensor for monitoring plant pathogen

Nanotechnology enables the development of highly sensitive and specific sensors by leveraging the unique properties of nanomaterials. These sensors can detect pathogens at extremely low concentrations, which is crucial for preventing crop diseases and minimizing losses. The primary advantage of using nano-sensors for pathogen detection is their ability to provide rapid, real-time, and accurate identification of pathogens, often with minimal sample preparation. Optical nano-sensors use light-based technologies to detect pathogens by monitoring changes in the optical properties of nanomaterials (such as fluorescence, absorption, or scattering) upon interaction with target molecules (i.e., pathogen-related biomarkers) (Shivashakarappa et al., 2022).

Electrochemical nano-sensors operate based on the changes in electrical properties (such as current, potential, or impedance) of a sensor material when it interacts with a target pathogen or its biomarkers (proteins, nucleic acids, etc.). Colorimetric nano-sensors change color in the presence of pathogens or their specific biomarkers. This technique is often easy to interpret and doesn't require expensive equipment, making it suitable for field testing. Magnetic nano-sensors use magnetic nanoparticles that interact with specific pathogen markers. These sensors detect changes in the magnetic properties (e.g., magnetic field or magnetization) when the nanoparticles bind to the target pathogen or pathogen biomarker (Vatankhah et al., 2022).

Nano-sensor for monitoring pesticides

Nano-sensors detect pesticide residues through interactions between the pesticide molecules and the functionalized surface of nanomaterials. These interactions cause measurable changes in the physical, chemical, or optical properties of the sensor, which can be quantified and analyzed to determine pesticide levels. The main types of nano-sensors for pesticide monitoring include optical, electrochemical, colorimetric, magnetic, and mechanical sensors. Surface Plasmon Resonance (SPR): SPR sensors use metal nanoparticles, typically gold or silver, to measure the shift in refractive index when pesticide molecules interact with the surface. This enables real-time, label-free detection of pesticides. Fluorescent Quantum Dots (QDs): Quantum dots are semiconductor nanocrystals that emit fluorescence when excited by light (Panoth et al., 2022). They can be functionalized with specific ligands (e.g., antibodies or aptamers) that bind to pesticide molecules, producing a detectable fluorescence signal. Localized Surface Plasmon Resonance (LSPR): LSPR-based sensors use metal nanoparticles that enhance light scattering or absorption when pesticide molecules bind to the surface, allowing for highly sensitive detection. Nano-sensors for pesticide monitoring hold tremendous promise for revolutionizing the way pesticides are managed in agriculture. By offering real-time, highly sensitive, and portable solutions for detecting pesticide residues in various environments, nano-sensors can contribute to safer, more sustainable agricultural practices, improved food safety, and enhanced environmental protection. Despite some challenges, ongoing research and technological advancements are expected to enhance their effectiveness and affordability, making them a key tool in the future of precision agriculture and food safety monitoring (Talari et al., 2021).

Crop Production

Nanoparticle based smart delivery for micronutrient and growth

The use of nanoparticle-based delivery systems for the targeted and controlled release of micronutrients and growth regulators (also known as plant hormones) has emerged as an innovative approach in precision agriculture. These nano-enabled delivery systems offer several advantages, including enhanced bioavailability, controlled release, and reduced environmental impact. Nanotechnology can revolutionize the way we manage plant nutrition and growth regulation, improving crop productivity, quality, and sustainability (Arshad et al., 2021). A smart delivery system refers to a technology that can deliver micronutrients and growth regulators to plants in a controlled, targeted, and efficient manner. Nanoparticles, due to their small size, large surface area, and ability to be functionalized with various materials, can be engineered to carry and release bioactive agents in a controlled manner. These systems can improve the uptake of micronutrients and growth regulators, ensuring that plants receive optimal doses at the right time. Nanoparticles can be engineered to deliver micronutrients (such as iron, zinc, manganese, copper) and growth regulators (such as auxins, gibberellins, cytokinins) to plants via different mechanisms.

Slow and Controlled Release: Nanoparticles can be designed to release their payloads over time, which reduces the frequency of application and ensures that micronutrients and growth regulators are available to plants for an extended period. pH or Stimulus-Responsive Release: Some nanoparticles are engineered to respond to environmental stimuli such as changes in pH, temperature, or light. For example, certain plant tissues have specific pH conditions that can trigger the release of nutrients or hormones from the nanoparticles. Nanoparticle-based smart delivery systems represent a promising frontier in agricultural technology. By enhancing the uptake and controlled release of micronutrients and growth regulators, these systems offer significant benefits in terms of crop productivity, sustainability, and environmental protection. While there are still challenges to overcome, particularly in terms of cost, toxicity, and regulatory approval, the potential of these systems to revolutionize plant nutrition and growth management is immense. Ongoing research and development in this field will likely lead to more efficient, sustainable, and precision-based farming practices in the near future (Arora et al., 2024).

Nanopesticides and nanoherbicides

The development of nanopesticides and nanoherbicides represents a cutting-edge approach to pest and weed management in agriculture. By leveraging the unique properties of nanomaterials, these advanced formulations offer enhanced efficacy, precision, and sustainability compared to traditional chemical pesticides and herbicides. The use of nanoparticles in agrochemicals holds immense potential for improving crop protection while reducing environmental impact, human toxicity, and the development of resistance (Wang et al., 2022). Nanopesticides and nanoherbicides represent an exciting frontier in agricultural technology. By harnessing the unique properties of nanomaterials, these smart delivery systems offer several advantages over conventional pesticides and herbicides, including improved efficiency, targeted delivery, reduced environmental impact, and enhanced pest and weed control.

However, there are significant challenges that need to be addressed before their widespread commercial adoption, including regulatory hurdles, toxicity concerns, and environmental impact assessments. As research advances and more real-world data becomes available, nanopesticides and nanoherbicides have the potential to significantly improve

Agriculture Engineering

Stress tolerance

In the face of climate change, increasing global population, and the growing demand for food, improving stress tolerance in crops is a critical priority for agriculture engineering. Stress tolerance refers to a plant's ability to withstand various abiotic stresses such as drought, salinity, extreme temperatures, soil compaction, and nutrient deficiencies, as well as biotic stresses like pest infestations and diseases. Engineering crops and agricultural practices to better cope with these stresses is essential for maintaining agricultural productivity, ensuring food security, and promoting sustainable farming. Agricultural engineering can significantly contribute to enhancing stress tolerance through biotechnological innovations, smart irrigation systems, controlled environments, soil management strategies, and more. Biotechnological tools, particularly genetic engineering and genomic breeding, play a vital role in enhancing the stress tolerance of crops (Nawaz et al., 2023). Genetic modifications can make plants more resistant to adverse environmental conditions. Genetic modifications can help crops cope with water stress by enhancing their ability to retain water, reduce transpiration, or improve root structure.

For example, genes associated with abscisic acid (ABA), a plant hormone that regulates water stress responses, can be introduced to enhance drought resistance. Salinity stress is a major concern in areas with high evaporation rates and saline groundwater. Engineering plants to tolerate high salt concentrations can increase agricultural productivity in saline-prone areas. With increasing temperatures due to climate change, crops need to be engineered for heat tolerance (Wu and Bose, 2024). Heat stress affects crop yield by disrupting key physiological processes such as photosynthesis, cell division, and seed development.

Biosensors for precise weed control

Weed control is one of the most significant challenges in modern agriculture, particularly as herbicide resistance increases and environmental concerns around chemical pesticide use grow. Biosensors offer an innovative, environmentally friendly, and precise solution for weed management. These sensors can detect and differentiate between crops and weeds in real-time, enabling targeted, site-specific interventions (Guo et al., 2024). This allows for more efficient use of herbicides, minimizes crop damage, reduces environmental impact, and can significantly improve crop yields. Biosensors for weed control are devices that use biological materials or biological reactions to detect the presence of weeds in agricultural fields. They operate based on the principle of recognizing specific biological markers, such as chemical compounds, proteins, or molecular structures that are unique to weeds but not present in crops.

Biosensors for precise weed control represent a transformative advancement in the field ofprecision agriculture. By enabling early detection, targeted herbicide application, and non-chemical weed control methods, biosensors can significantly enhance the efficiency and sustainability of weed management practices. These technologies hold the potential to reduce herbicide use, combat herbicide resistance, and improve crop yields, all while minimizing environmental impact. As biosensor technology continues to evolve, it promises to become an integral part of smart farming systems, contributing to more sustainable and efficient agricultural practices for the future (Zhang et al., 2024).

Soil improvement

Soil is a fundamental resource for agriculture, serving as the medium in which plants grow, obtain nutrients, and develop root systems. However, soil quality can degrade due to factors like erosion, nutrient depletion, compaction, salinity, and pollution. In the face of challenges like climate change, increased agricultural demand, and urbanization, improving soil health and productivity is critical for ensuring food security and promoting sustainable farming practices (Li et al., 2023). Agricultural engineering offers innovative and practical approaches to soil improvement. These include techniques that enhance soil structure, fertility, moisture retention, and nutrient availability. Here’s a detailed exploration of soil improvement methods and technologies in agricultural engineering. Soil erosion is a major concern that leads to the loss of topsoil, which is vital for crop production. Erosion occurs due to wind, water, and human activities like overgrazing and deforestation.

The implementation of effective soil erosion control strategies is essential for maintaining soil health and fertility. Fertile soil provides crops with essential nutrients like nitrogen, phosphorus, potassium, calcium, magnesium, and micronutrients. Agricultural engineers use several techniques to replenish and maintain soil fertility. Bio-fertilizersare natural fertilizers that contain living microorganisms capable of promoting plant growth by enhancing nutrient availability in the soil.

Soil improvement is a multifaceted process that requires a combination of engineering, biological, and management techniques to ensure healthy, productive soils for sustainable agriculture (Hou et al., 2020). Agricultural engineering plays a crucial role in developing technologies and systems for improving soil structure, fertility, water retention, and nutrient availability. By adopting these innovative techniques, farmers can enhance soil health, reduce environmental degradation, and increase crop yields, ultimately contributing to food security and sustainable farming practices.

Future perspectives

Precision agriculture will drastically improve resource use efficiency, reduce environmental degradation (e.g., through precise pesticide application), and increase crop yields. It will be especially beneficial for smallholder farmers in developing countries by making cutting-edge technology more accessible and affordable. Biotechnology will help address the global challenges of food security, resource scarcity, and climate change by developing crops that are more resilient, nutrient-dense, and environmentally friendly. The future of agricultural engineering is bright, driven by technological advancements, sustainability goals, and the need for innovative solutions to feed a growing global population.

Precision farming**,** biotechnology**,** sustainable practices**,** climate-smart agriculture**,** automation**,** and urban farming will transform agriculture into a highly efficient, sustainable, and resilient industry. By integrating cutting-edge technologies and focusing on long-term environmental health, agricultural engineering will play a crucial role in addressing global challenges such as food security, climate change, and resource conservation.

Conflict of interest statement

Authors declare that they have no conflict of interest.

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