

Transforming waste into wealth: Leveraging nanotechnology for recycling agricultural byproducts into value-added products

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ABSTRACT

The extensive generation of agricultural waste worldwide poses significant environmental challenges. Traditional disposal methods, such as crop burning, contribute to severe air pollution and ecological degradation. Current agricultural waste management strategies often fail to fully utilize the potential of these residues for conversion into valuable resources. This review highlights the transformative role of nanotechnology in upcycling agricultural waste into high-value, sustainable products, thereby advancing the circular economy. Innovations such as nanocatalysts, biodegradable nanomaterials, and nano-enabled agrochemicals have opened efficient pathways for converting agricultural residues into nanomaterials like nanocellulose, biopolymers, bioplastics, nanofertilizers, and biochar. These technologies provide eco-friendly alternatives to conventional materials while addressing pressing global sustainability challenges. Despite technical, regulatory, and market barriers, integrating nanotechnology into agricultural waste management offers immense potential to minimize waste, reduce environmental impacts, and create economic value. This review emphasizes the need for supportive policies, collaborative efforts between industry and academia, and increased public awareness to foster the widespread adoption of nanotechnological innovations. By reimagining agricultural waste as a valuable resource, nanotechnology can drive sustainable development and enhance resource efficiency, paving the way toward a greener and more resilient future.

1. Introduction

With the world's population projected to surge to 9.7 billion by 2050, a sharp increase from 7.8 billion today, the global agricultural sector faces the immense challenge of producing 70 % more food to meet the escalating demand (Population. United Nations, 2023). However, this need for increased output comes amid a rapidly changing climate that amplifies extreme weather, threatening agricultural productivity worldwide. These dual pressures of feeding a growing population while contending with climate change, have intensified stress on agricultural systems, where advancements in yield are often accompanied by a growing environmental burden in the form of agricultural waste. Crop residues, animal byproducts, and food-processing waste are accumulating at unprecedented rates, further straining ecosystems and creating a pressing waste management challenge (Divyabharathi et al., 2024; Sun et al., 2024a, b).

Mismanagement of agricultural waste is a major global issue, with

conventional disposal methods like incineration, open dumping, and poor landfill practices not only depleting valuable resources but also causing severe ecological harm. These practices generate greenhouse gases and pollutants, degrading soil health and intensifying climate change. (Koul et al., 2022). For example, the burning of crop residues emits significant quantities of CO₂, CH₄, and NO_x, which harm air quality, affect public health, and contribute to the global climate crisis (Odubo and Kosoe, 2024). The management of agricultural waste is a major global challenge, with certain regions being identified as critical hotspots for high waste production. The impact is particularly severe in regions with high agricultural waste and limited waste management systems, such as China, India, and parts of Africa, where waste production often exceeds the capacity for sustainable disposal (Duque-Acevedo et al., 2020; Koul et al., 2022).

India, the second-largest producer of agricultural waste worldwide, illustrates the severity of this issue. With over 130 million tonnes of paddy straw alone produced annually, much of which is burned or

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discarded, the environmental consequences are severe (Koul et al., 2022; Pandit et al., 2024). The emissions from burning residues degrade air quality, undermine soil fertility, and waste valuable biomass that could otherwise fuel economic growth and sustainable development (Jones et al., 2021).

The concept of a circular bioeconomy, however, offers a promising vision of agricultural waste not as a problem, but as a resource to drive sustainability and innovation. By applying circular principles, agricultural residues can be upcycled into high-value products such as biofuels, bioplastics, bio-based chemicals, and even food and feed supplements. This transformation not only addresses the twin challenges of waste management and resource scarcity but also presents an economic opportunity to reduce waste, minimize pollution, and drive innovation (Mujtaba et al., 2023).

In this context, nanotechnology emerges as a transformative force, fundamentally reshaping the approach to manage agricultural waste. Advanced nanomaterials and nano-enabled processes are opening doors to efficient, eco-friendly conversion of waste into valuable resources like biofuels, bioplastics, and nanocomposites (Behl et al., 2022; Dalbanjan et al., 2024). Integrated within the circular bioeconomy, nanotechnology transforms agricultural waste into economic assets, aligning environmental conservation with economic growth under the “waste-to-wealth” paradigm (Morganti, 2015). As represented in Fig. 1, nanotechnology facilitates a systematic approach to agricultural waste management, encompassing collection, processing, raw material generation, production, use, and recycling. It enhances material recovery efficiency, drives the conversion of waste into high-value products such

as bioplastics, biofuels, and biochemicals, and supports the design of advanced materials for sustainable applications. This holistic framework underscores the role of nanotechnology in fostering sustainability and resource optimization within the bioeconomy.

This review explores how nanotechnology can redefine agricultural waste as a catalyst for sustainability and economic growth, positioning it as a core solution to environmental challenges and as an engine of opportunity in a greener, circular bioeconomy. By viewing agricultural waste not as an issue, but as a valuable input for sustainable innovation, we unveil a nanotech-driven path towards a resilient future where, waste fuels both growth and conservation simultaneously.

2. Agricultural waste: a global resource ready for innovation

Agricultural waste and its by-products consist of plant and animal remnants that remain unutilized after food or feed production processes (Gontard et al., 2018). This broad category includes materials from various stages of food production and consumption, presenting a unique opportunity for sustainable resource utilization. The following sections categorize these materials and highlight global hotspots for agricultural waste, underscoring both the challenges and the innovation opportunities (Gontard et al., 2018; Kumar et al., 2023)

2.1. Types of agricultural waste

Agricultural waste can be broadly categorized based on the origin and nature of the materials. The main types include:

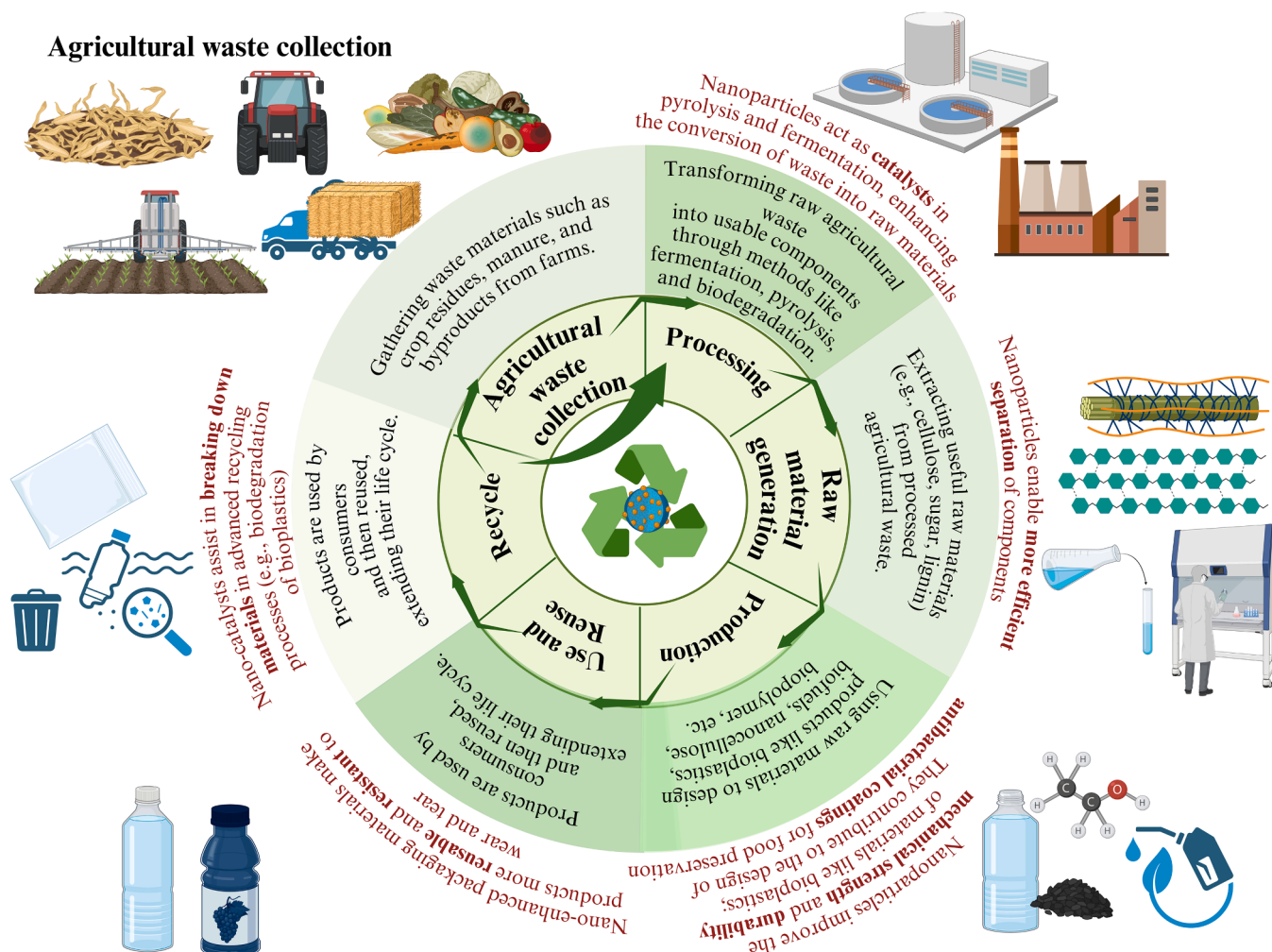


Fig. 1. Nanotechnology-driven circular approach for sustainable management and valorisation of agricultural waste in the bioeconomy.

2.1.1. Crop residues

These are the plant parts that remain after the harvesting process, including stems, leaves, and stalks. Common examples include:

- **Straw:** Refers to the dry stems and foliage of cereal crops, such as rice, wheat, and barley.
- **Stalks:** These are woody or fibrous stems found in crops like corn, sugarcane, and cotton.
- **Chaff:** The husks and other non-consumable components of cereal grains.
- **Leaves:** The flat, green structures responsible for photosynthesis in plants.
- **Roots:** The subterranean parts of plants that absorb water and nutrients.

2.1.2. Food processing waste

This category includes by-products produced during the processing of agricultural goods, such as peels from fruits and vegetables, coffee grounds, and whey from dairy products (P. Sharma et al., 2021). Common examples are:

- **Fruit and vegetable skins:** The outer layers of fruits and vegetables, such as apple skins, potato peels, and banana skins.

- **Coffee residues:** The byproducts left after brewing coffee beans.
- **Tea remnants:** The used leaves left over from tea production.
- **Dairy byproduct:** The liquid that separates from milk during cheese production.
- **Brewing grains:** The residual grains produced during the beer brewing process.
- **Poultry plumage:** Feathers naturally shed by birds, such as chickens and turkeys.

2.1.3. Livestock waste

Livestock waste includes manure, bedding materials, and the remains of animals raised for food or other purposes (Nweze et al., 2023).

2.1.4. Other categories

- **Husk:** The outer protective covering of grains such as rice and oats, typically removed during the milling process. These husks can be repurposed for use as animal feed or compost.
- **Shells:** The hard exteriors of nuts, seeds, and shellfish, which can serve various purposes, including enhancing soil, composting, or processing into lime (Karić et al., 2022).

The categories mentioned above represent just a fraction of the

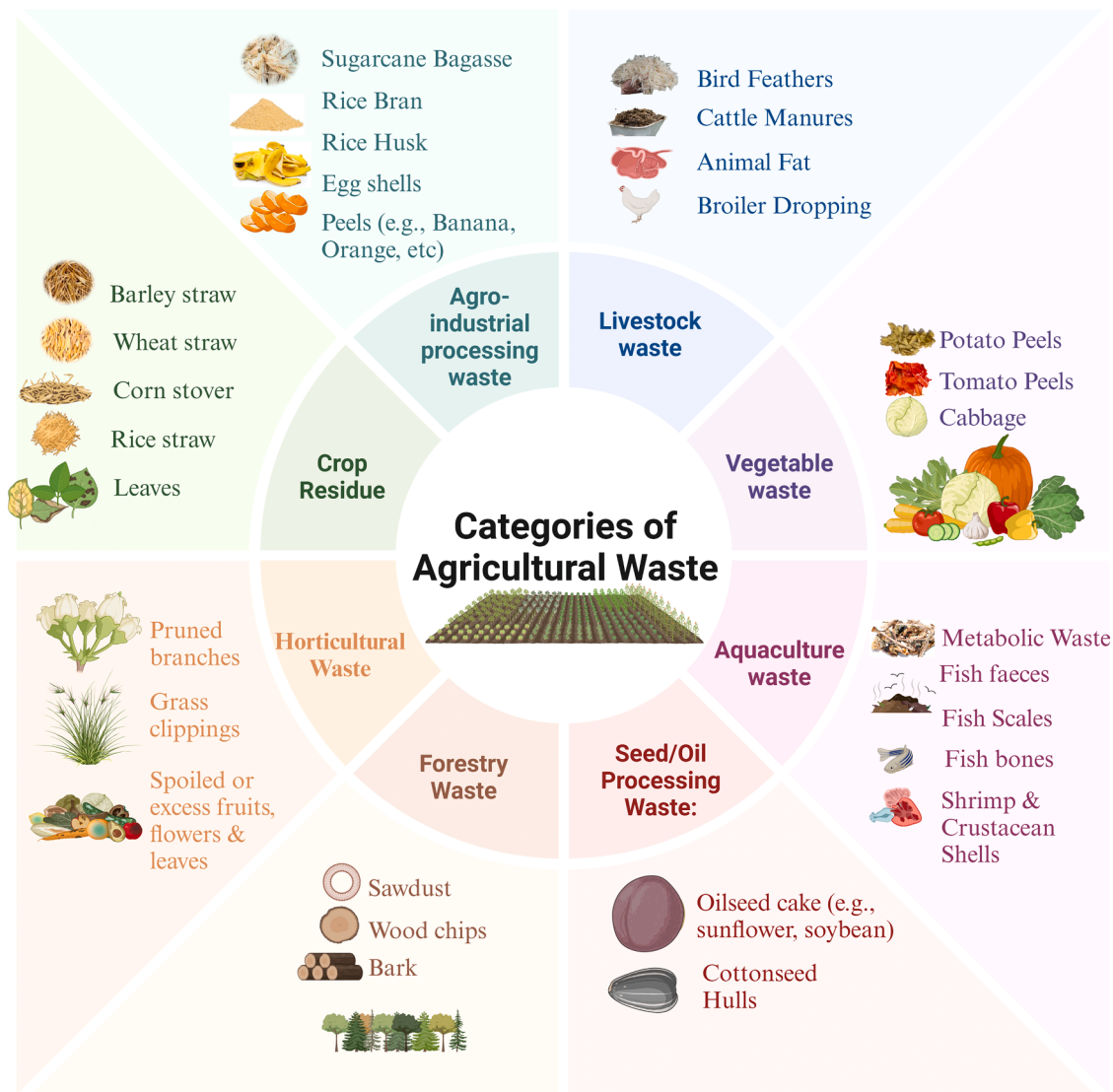


Fig. 2. Different kinds of agriculture-based waste.

diverse agricultural waste generated annually. Fig. 2 illustrates the various types of agricultural wastes. Effective management of these materials is essential for protecting the environment and promoting sustainable agricultural practices.

2.2. Agricultural waste hotspots and global distribution

Certain regions of the world produce large quantities of agricultural waste due to intensive farming practices and high crop production usually known as hotspots (Fig. 3). These hotspots, which contribute significantly to the global waste burden, represent both a challenge and an opportunity for developing effective waste management strategies (Onu and Mbohwa, 2021; Teigiserova et al., 2019). Key regions include:

- **Asia:**
 - o China: The world's largest producer of rice, China generates vast amounts of rice straw, as well as considerable quantities of wheat straw and corn stover. (Alengebawry et al., 2023).
 - o India: A major producer of rice and wheat, India also produces large volumes of sugarcane bagasse and cotton stalks, contributing significantly to its agricultural waste output. (Chauhan et al., 2022).
- **North America:**
 - o United States: Known for its extensive corn and wheat farming, the U.S. produces significant amounts of agricultural waste, including corn stover and soybean residue (Battaglia et al., 2024; Taghizadeh-Alisaraei et al., 2023).
 - o Canada: Similar to the U.S., Canada's large-scale wheat and corn farming generates considerable waste, along with by-products from canola and barley production (X. Li et al., 2012; Shanmugam et al., 2024).

- **Europe:**
 - o France: As a major agricultural producer in Europe, France generates substantial waste from its cereal crops, vineyards, and orchards (Redlingshöfer et al., 2017).
 - o Germany: Germany's farming practices, which include growing crops like wheat, barley, and rapeseed, produce large quantities of agricultural waste. The dairy and livestock sectors also contribute to waste generation (Sobczak et al., 2022).
 - o Spain: Agricultural waste from cereals, vegetables, fruits, and olive and citrus cultivation is prevalent in Spain (Duque-Acevedo et al., 2023; Pardo et al., 2017).
- **Latin America:**
 - o Brazil: A leading producer of sugarcane, Brazil generates large amounts of bagasse, in addition to waste from soybean and corn cultivation (Hiranobe et al., 2024).
 - o Argentina: Known for generating agricultural waste from its soybean, corn, and wheat crops, Argentina also produces waste from sunflower and cotton cultivation (Nath et al., 2023a).

These regions hold immense potential for converting agricultural waste into valuable products. Embracing technological innovations, such as nanotechnology, could transform these by-products into valuable resources that support environmental sustainability and economic growth, demonstrating the global potential of agricultural waste as a resource.

3. Environmental challenges and economic impacts of agricultural waste

Agricultural waste, generated from farming activities, poses significant environmental and economic challenges. Poor management of this

Agricultural Waste Hotspots



Fig. 3. Global hot spots for agricultural waste.

waste not only contributes to environmental degradation but also results in missed opportunities for economic gain. The following sections explore these impacts in greater detail.

3.1. Environmental challenges

The inadequate disposal and management of agricultural waste leads to various environmental issues that affect soil, air, and water quality:

- **Landfill overuse and soil degradation:** Disposing agricultural waste in landfills consumes valuable space that could be used for productive purposes, such as farming. Moreover, the accumulation of organic waste in landfills accelerates soil degradation in surrounding areas, which reduces fertility and impacts agricultural productivity (Arora et al., 2023; Düring and Gäth, 2002).
- **Methane emissions and climate change:** The decomposition of agricultural waste, particularly organic materials like plant and animal by-products, generates methane in landfills. As a potent greenhouse gas with a global warming potential 25 times greater than carbon dioxide, methane significantly contributes to climate change, further affecting global agricultural yields (Kiehbadrudinezhad et al., 2024; Neri et al., 2023).
- **Soil quality decline:** Unmanaged agricultural residues like straw and stalks, when left in fields or improperly disposed of, lead to soil degradation. These residues, which could naturally return nutrients to the soil, instead deplete valuable minerals and organic matter, undermining soil health and productivity (Cherwoo et al., 2023; Halko et al., 2023; Verma et al., 2024).
- **Air pollution from open burning:** In many regions, especially in developing countries, the open burning of agricultural waste is a common practice. This method releases harmful pollutants into the air, including particulate matter (PM), carbon monoxide (CO), and volatile organic compounds (VOCs), all of which degrade air quality and pose serious health risks to local communities (Anokye et al., 2024; P. Das et al., 2024; Mondal and Chattopadhyay, 2024; Pradhan et al., 2024).
- **Water pollution from runoff:** Improper management of agricultural waste can lead to water pollution. Nutrient-rich waste from crop residues and animal by-products can runoff into water bodies, causing eutrophication and disrupting aquatic ecosystems (Akinbile et al., 2016; Khan et al., 2024).

3.2. Economic impact of neglected agricultural waste

The failure to effectively utilize agricultural waste results in significant economic losses for farming communities and the broader economy:

- **Resource inefficiency and increased costs:** When agricultural waste is left to decompose or be discarded, valuable resources, such as nutrients and organic matter, are wasted. This inefficiency drives up costs for farmers who must purchase additional fertilizers and soil enhancers to maintain soil quality and productivity (Kesari et al., 2021).
- **Rising public costs:** Governments often bear the financial burden of addressing the environmental and health consequences of poorly managed agricultural waste. Funds spent on remediating polluted environments and dealing with health issues related to waste could be better used to support sustainable agricultural practices and economic growth (Wu et al., 2024).
- **Missed Revenue from By-products:** Agricultural waste, such as crop residues, animal manure, and food processing by-products, presents untapped potential for value creation. Without proper utilization, these materials are wasted, and the opportunity to generate additional income or develop sustainable products is lost.

4. Redefining agricultural by-products: a nanotechnology-driven perspective

Agricultural waste has traditionally been seen as an environmental challenge, but with the advent of nanotechnology, these by-products are now recognized as a valuable resource with significant economic potential. As illustrated in Fig. 4, nanotechnology offers transformative pathways for converting agricultural waste into high-value products, supporting sustainable waste management practices and offering extensive cross-sector applications in fields such as healthcare, electronics, and environmental conservation. These innovations not only reduce the ecological footprint of agriculture but also create economic opportunities for farmers and industries, facilitating a circular, profitable, and sustainable agricultural system (Aydin et al., 2023; Devi and Lakshmi, 2018).

4.1. Conversion of agricultural waste into value-added products by the hands of nanotechnology

Through the manipulation of materials at the nanoscale, nanotechnology has the potential to improve the efficiency of waste conversion processes and facilitate the development of high-performance products derived from previously discarded agricultural by-products. The following section outlines how nanotechnology is being utilized in several significant ways to transform agricultural waste into products of greater value:

4.1.1. Biofuels and energy production from agricultural waste

The incorporation of nanotechnology in the production of biofuels from agricultural waste is transforming the energy landscape. Agricultural by-products, abundant in cellulose, hemicellulose, and various biomolecules, serve as a crucial resource for biofuel production. The application of nanotechnology in this context utilizes nanoparticles as catalysts, which significantly enhance the efficiency of biomass conversion into biofuels. For example, metallic, magnetic, and metal oxide nanoparticles create distinctive active sites that promote metabolic reactions, thereby increasing biofuel output (Nath et al., 2023b; Sakthivel et al., 2024; Sher et al., 2024). This cutting-edge method not only tackles the issue of managing agricultural waste but also supports sustainable energy generation, decreasing dependence on fossil fuels and minimizing carbon emissions. The potential of different agricultural wastes employed as feedstock for biofuel production is mentioned in Table 1.

Also, nanotechnology plays a crucial role in improving the pretreatment processes of agricultural waste, thereby enhancing the efficiency and sustainability of biomass conversion. In this framework, nanoparticles serve as catalysts to decompose the intricate structures of lignocellulosic biomass, which consists of cellulose, hemicellulose, and lignin. Various types of nanoparticles, including metallic, magnetic, and metal oxide varieties, create distinctive active sites that promote the hydrolysis of biomass into fermentable sugars. Furthermore, carbon-based nanomaterials, such as carbon nanotubes and nanofibers, provide extensive surface areas for enzyme immobilization, which significantly boosts the efficiency of enzymatic reactions. The incorporation of nanotechnology into the pretreatment of agricultural waste leads to more effective processes, minimizing the reliance on harsh chemicals and reducing energy consumption, ultimately resulting in increased yields of biofuels and other valuable bioproducts (Gaikwad et al., 2018; Ingle et al., 2017, 2020; Saxena et al., 2023).

Fig. 5 illustrates the integration of nanotechnology into the biofuel production process from agricultural waste. It highlights key pathways and applications of nanoparticles at various stages, including pretreatment (e.g., enzymatic hydrolysis and acid/alkali hydrolysis), bioconversion processes (e.g., fermentation, transesterification), and chemical and physical modifications to produce value-added biofuels. The figure also demonstrates how nanotechnology enhances the efficiency, yield, and sustainability of biofuels such as bioethanol, biodiesel, biobutanol,

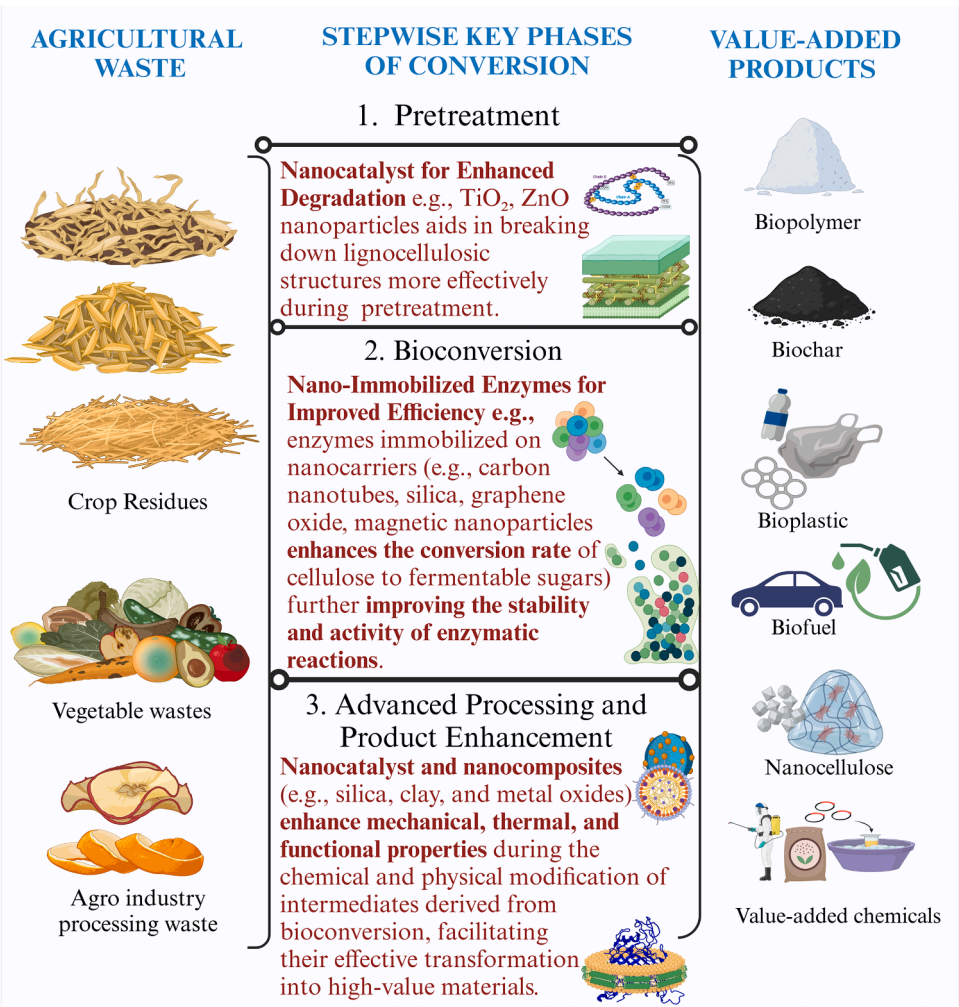


Fig. 4. Schematic representation of conversion of various agricultural waste into high-value products.

Table 1
Potential of different agricultural wastes for biofuel production.

Agricultural residue	Bioethanol	Biodiesel	Biobutanol	Biomethanol	Reference(s)
Rice straw	12–29.1 L/kg	96.49 %	75.0–95.6 g/kg	42.7 %	(Akhtar et al., 2017; Cheng et al., 2012; Poy Andreu, 2024; Saetiao et al., 2023)
Sugarcane bagasse	23.2–59.1 L/kg	90.1 %	1.95 g/L	3.09 wt%	(Cheng et al., 2012; Hassa et al., 2024; Hu, 2009; Kasmuri et al., 2019)
Barley straw	11.9–46.0 L/kg	51.87 %	13.3 g/L	-	(Bhatia et al., 2019; Han et al., 2013; Nandhini et al., 2023)
Corn stover	40–55.27 L/kg	86.2 ± 2 mg/g	12.63 g/L	64.79 %	(Adelabu et al., 2019; Detchusananard et al., 2024; Luo, Shi, et al., 2023; Luo, Zhao, et al., 2023)
Wheat straw	11.8–71.2 L/kg	80 mg/g	14.2 g/L	-	(Morikawa et al., 2014; Valdez-Vazquez et al., 2015; Yuan et al., 2018)
Orange peel	6 %	5.8 g/L	0.35 g/g	28.3 g/L	(Carota et al., 2020; Joshi et al., 2015; Kamboj and Ms, 2021; Saadatinavaz et al., 2021)
Apple pomace	8.44 %	84.6 %	10 g/dm ³	-	(Hijosa-Valsero et al., 2017; Karatay et al., 2022)
Oil palm fruit	37.8 %	14.5 %	-	21.33 g/L	(Amin et al., 2024; Kim and Kim, 2013; Prihatiningtyas et al., 2024)
Barley straw	250–410 L/MT	-	30.8 g/L	-	(Nabila et al., 2024; Raut et al., 2021)
Cassava	180 mL/Kg	82 %	0.11 g/L/h	-	(Johnravindar et al., 2021; Lu et al., 2010; Waseem et al., 2024)
Sugarcane straw/bagasse	2.769 g/L (0.353 % v/v)	87 %	47.5 L/T	19.28 mM	(Cortés-Peña et al., 2024; Ruan et al., 2024; Souza et al., 2024)

and biohydrogen. These advancements demonstrate how nanotechnology enhances the efficiency, yield, and sustainability of biofuel production pipelines.

Future research can explore hybrid catalytic systems that combine metallic and carbon-based nanostructures to further boost conversion efficiency in biofuel production. This approach could involve the creation of bimetallic or trimetallic nanoparticles, which provide enhanced active sites and allow more efficient electron transfer, expediting

biomass breakdown and fuel generation. Additionally, nanotechnology could develop "nano-enzymes" or "artificial enzymes," designed to mimic biological enzymes but with heightened stability and specificity, to catalyze biofuel production from a wider range of agricultural waste types. Innovations in nanoparticle design, such as surface modifications that allow nanoparticles to withstand harsher operating conditions, would also increase the viability of biofuel production in diverse environments, making biofuels a more accessible and sustainable energy

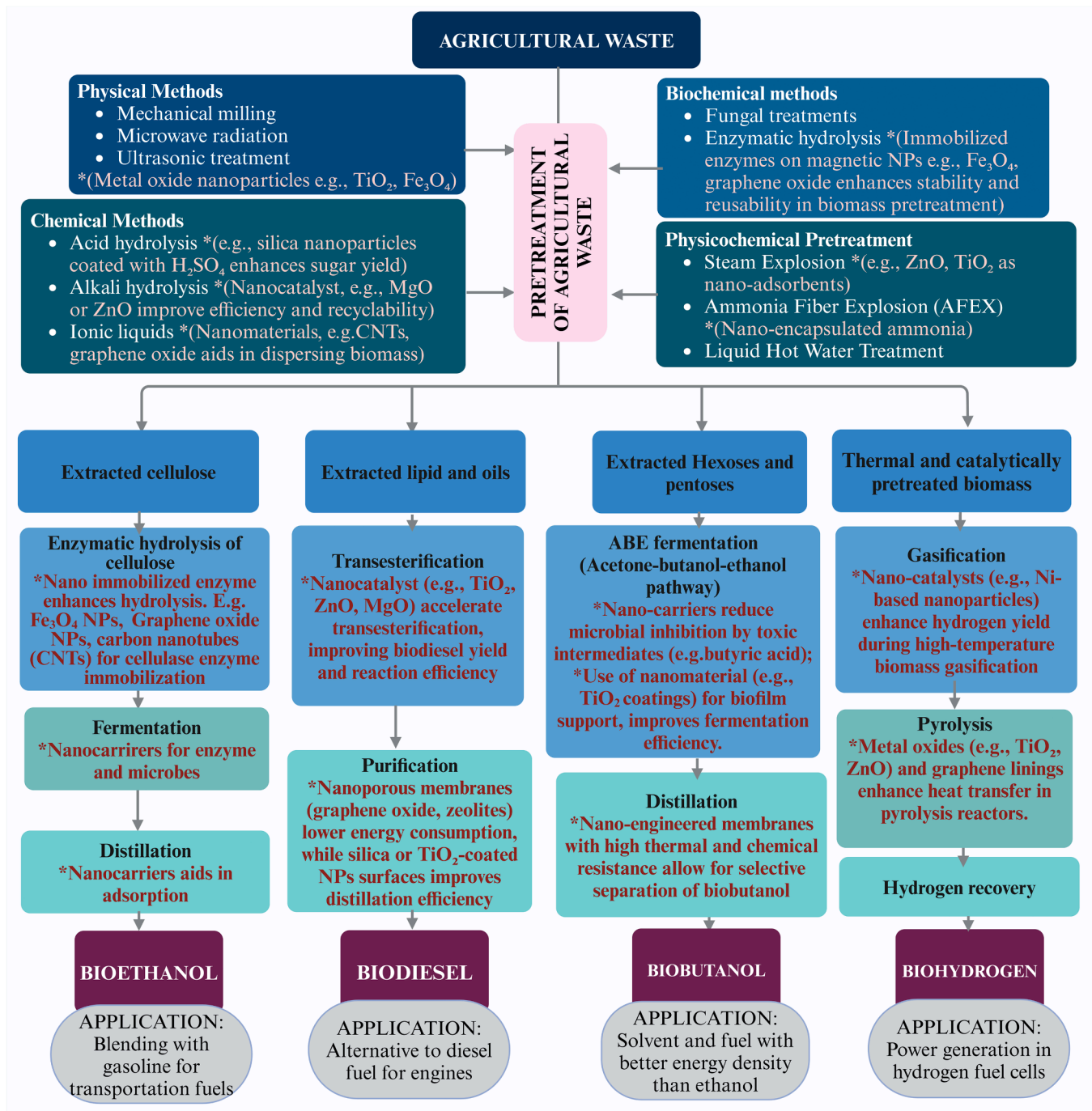


Fig. 5. Comprehensive pathways for biofuel production from agricultural waste utilizing nanotechnology interventions.

option worldwide.

4.1.2. Nano fertilizers from agricultural waste

Nanofertilizers, produced from nutrient-rich agricultural by-products, provide a revolutionary alternative to conventional fertilizers with distinct advantages:

- **Controlled release:** Nanofertilizers ensure a sustained nutrient release, optimizing plant uptake while reducing leaching and runoff, thus protecting surrounding ecosystems.
- **Enhanced Absorption:** With a small particle size, nanofertilizers penetrate plant cells more effectively, improving nutrient uptake and crop yield.

- **Environmental Impact:** By repurposing waste as fertilizers, agricultural systems can reduce reliance on synthetic products, enhancing sustainability and promoting circularity.

Nanofertilizers offer a sustainable alternative to traditional chemical fertilizers (Nongbet et al., 2022). Their small particle sizes and large surface areas enhance nutrient absorption and utilization efficiency in plants (Meena et al., 2017). By reducing particle size, the number of particles per unit area increases, promoting better interactions and nutrient uptake (Liscano et al., 2000). These nanomaterials can serve as both macro-nutrients (Feizi et al., 2013) and micro-nutrients (Mukherjee et al., 2016), while also acting as carriers for nutrient delivery. The process of converting agricultural waste into nano and

micro-sized particles improves absorption rates. This eco-friendly approach involves collecting and processing agricultural waste such as crop residues and animal manure followed by nutrient extraction through chemical or biological methods. Nanoparticles are synthesized using green techniques or chemical methods, encapsulating nutrients with materials like carbon nanotubes and graphene. To ensure controlled nutrient release, they are coated with biocompatible substances (Batool et al., 2024). These nanofertilizers undergo quality control to assess their nutrient composition and ecological impacts. Field experiments evaluate their effectiveness in improving crop productivity and soil health. This method optimizes nutrient delivery while minimizing environmental contamination from leaching and runoff. By repurposing agricultural byproducts, nanofertilizers promote sustainability and reduce dependence on synthetic fertilizers, offering a viable solution for increasing agricultural output and addressing environmental issues (Puglia et al., 2021). In a study by Smitha et al., (2024) they effectively utilized sugarcane bagasse, to synthesize and cap nano calcium borate (NCB) particles (size of 117.7 nm). They found that these nanoparticles significantly improved seed germination, root length, and vigor index, demonstrating their efficacy as nanobiofertilizers. The study deduced that the optimal concentration for seed priming was NCB@0.025, highlighting its potential for enhancing agricultural productivity. They concluded that sugarcane bagasse is a sustainable and biodegradable resource for synthesizing functional nanoparticles, contributing to eco-friendly fertilizer development.

Future studies could evaluate crop-specific formulations, optimized through precision agriculture technology. As nanofertilizer technology advances, tailored crop-specific formulations are expected to emerge, optimizing nutrient delivery based on each plant's growth stage and specific nutrient requirements. Coupling nanofertilizers with precision agriculture technology like drones or sensors that detect soil deficiencies in real-time could enable dynamic, site-specific fertilizer application, ensuring that nutrients are released only where needed. Such innovations would minimize wastage, reduce environmental impacts, and help prevent nutrient runoff, a key contributor to waterway eutrophication. Another promising area is the development of biodegradable nanofertilizer carriers derived from renewable agricultural waste sources, which could decompose seamlessly after nutrient delivery, further enhancing environmental sustainability. These advancements would not only improve crop yields and soil health but also offer farmers economic benefits through efficient resource use and decreased reliance on synthetic fertilizers.

4.1.3. Agricultural waste-derived nanoparticles for pesticide delivery

Pesticides are substances that inhibit the development of pests, including weeds (Eskenazi et al., 2023). Nanotechnology is progressively exploited to transform agricultural waste into nanoparticle-based systems for pesticide delivery (Fu et al., 2022). These innovative systems offer enhanced efficiency and are more environmentally sustainable compared to traditional pesticides.

- **Targeted applications:** Nanoparticles encapsulate pesticide components, directing them toward specific pests, reducing the need for high chemical volumes, and decreasing environmental pollution (Nazeer et al., 2023; Zhong et al., 2024).
- **Biodegradable nanocarriers:** Agricultural waste-derived nanomaterials can act as carriers, breaking down harmlessly post-release, and addressing concerns of pesticide residue accumulation (Rani and Shanker, 2017; Zainab et al., 2024).

Joeniarti et al. (2019) formulated the neem leaf alcoholic extract into a nano-emulsion. This nano-emulsion was tested against *Spodoptera litura*. The characterization involved FTIR, UV, and DLS to measure the size of particles. The size of chitosan modified with succinic anhydride was found to be 319 nm. The mortality rate of *S. litura* significantly increases, reaching as high as 82 %, as compared to untreated foliage.

Furthermore, encapsulation improves its effectiveness, making it an outstanding pesticide. Similarly, in a study citrus peel essential oils were developed into a nano-emulsion containing polyethylene glycol (PEG) Nano-particles. This formulation underwent successful testing against the Tomato pest *Tuta absoluta*. The measured sizes for lemon essential oil nanoparticles (EO-NPs), mandarin EO-NP, and sweet orange EO-NP were 240 ± 2.51 nm, 212.05 ± 0.04 nm, and 216.6 ± 0.63 nm, respectively. There toxicity study in eggs suggested that the greatest mortality rate from the application of EO-NP was recorded at a concentration of 40 mg/mL. While toxicity in larvae in the case of sweet orange, the mortality rate increased twofold after 72 hours. The EO-NP formulation derived from mandarin exhibited the highest mortality rate among the larvae (Campolo et al., 2017).

Future work in this area could focus on developing “smart” nanoparticles that release pesticides in response to specific environmental triggers, such as pH shifts, temperature fluctuations, or pest secretions. For example, pH-sensitive nanocarriers could deliver pesticides when pests produce certain acidic or alkaline secretions, ensuring targeted release only in the presence of pests, thus sparing beneficial insects. Additionally, research could advance the development of biodegradable nanocarriers made from agricultural waste by-products, creating a fully circular pesticide system where carriers break down harmlessly after use. This smart, eco-friendly approach would substantially reduce chemical load in agricultural ecosystems, minimize the risk of pest resistance, and ultimately pave the way for precision pest management techniques that are safer for both crops and surrounding wildlife

4.1.4. Biochar and carbon nanomaterials derived from agricultural waste

Agricultural by-products like rice husks and coconut shells are converted into biochar and carbon nanomaterials, widely valued for various applications:

- **Activated carbon for water purification:** Biochar processed at the nanoscale exhibits high porosity and surface area, effectively removing pollutants from water. This sustainable approach contributes to both waste reduction and water treatment (Nazem et al., 2020; Nezafat et al., 2024).
- **Carbon nanotubes and graphene:** Agricultural biomass can be transformed into carbon nanomaterials, including carbon nanotubes (CNTs) and graphene (Zhou et al., 2022). These substances exhibit remarkable electrical conductivity, mechanical strength, and thermal characteristics. They find applications in energy storage systems (such as batteries and supercapacitors), electronic sensors, and structural components across diverse industries (Wang et al., 2018).
- **Soil improvement and carbon sequestration:** Biochar derived from agricultural waste enhances soil fertility and water retention while facilitating carbon sequestration in the soil (Wijitkosum and Jiwnok, 2019). When processed at the nanoscale, biochar exhibits improved properties that enhance its effectiveness in agricultural practices (Song et al., 2022).

In a study performed by Wijitkosum and Jiwnok (2019), the chemical composition and morphology of biochar produced from corncobs, cassava rhizomes, and cassava stems through slow pyrolysis at 500–600°C were analyzed. Corncob biochar had the highest carbon content, while cassava stem biochar exhibited the greatest surface area and total pore volume, enhancing its ion exchange capacity and water retention. The findings suggest that biochar from these biomass sources is suitable for soil amendment and carbon sequestration.

Soliman et al., (2024) provides a valuable focus on utilizing agricultural waste to produce biochar and nanobiochar. Their study used rice straw, palm fronds, and sugarcane residues as raw materials, demonstrating the potential of these agrowastes in creating effective biosorbents. They found that nanobiochar, significantly improved wastewater quality by reducing heavy metals and other contaminants.

They deduced that nanobiochar derived from sugarcane residues exhibited the highest adsorption efficiency among the tested materials. Additionally, they concluded that the practical application of nanobiochar not only enhances wastewater treatment processes but also promotes sustainable water management and agricultural practices. This work underscores the environmental and economic value of transforming agricultural residues into high-value nanomaterials.

Also, Rana et al. (2021) researched for the removal of pesticides from water using low-cost cellulose biomass-based derivatives. Results showed the environmental impact of pesticide residues and also evaluated the efficiency of various cellulose-based materials, including magnetite cellulose nanocomposites and activated carbons. Functionalized cellulose and activated carbons are found to be highly effective, with cellulose/MnO₂ photonanocatalysts being particularly efficient.

Biochar and carbon nanomaterials derived from agricultural waste have significant environmental value in carbon sequestration and soil amendment, addressing issues like soil degradation. Future research could explore more efficient and eco-friendly biochar production techniques. The development of biochar-based carbon nanomaterials holds immense potential for addressing environmental issues, particularly in soil restoration and water purification. Future studies could focus on optimizing biochar production techniques, such as hydrothermal carbonization and microwave-assisted pyrolysis, to yield carbon materials with even greater adsorption capacities and porosity. Additionally, there is significant promise in exploring biochar functionalization, where specific chemical groups or nanostructures are added to enhance pollutant removal in water treatment applications. Carbon nanomaterials derived from biochar could also be refined to serve as energy storage solutions, such as in lithium-ion batteries, where their lightweight and conductive properties could improve battery efficiency and longevity. This dual-purpose strategy not only transforms waste into valuable materials but also creates sustainable technologies for critical needs like clean water and renewable energy.

4.1.5. Production of nanocellulose from Agricultural Residues

Nanocellulose extracted from crop stalks and husks holds unique mechanical properties, lightness, and high surface area, making it suitable for a range of industries (Picot-Allain and Emmambux, 2023).

- **Biodegradable packaging:** Nanocellulose offers a sustainable alternative to plastic, helping reduce plastic waste while creating eco-friendly packaging (Fahma et al., 2021).
- **Reinforcement in composites:** Nanocellulose-enhanced composites exhibit greater strength and resilience, suitable for applications in construction, automotive, and aerospace industries (Ferreira et al., 2019; Nurazzi et al., 2022).
- **Medical and Pharmaceutical Applications:** Due to its biocompatibility, nanocellulose is effective in drug delivery, wound healing, and tissue engineering applications (Kupnik et al., 2020).

The study by Ariaenejad et al., (2023) highlights the effective use of sugar beet pulp (SBP) for synthesizing a bio-based Fenton-like nanocatalyst by incorporating Fe₂O₃ nanoparticles onto nanocellulose (NC) surfaces. Their study demonstrated that SBP-derived NC, prepared under optimized acid hydrolysis conditions, had superior properties, including high crystallinity (56.7 %), larger surface area, and enhanced surface charge compared to quinoa husk-derived NC. They found that the SBP-based nanocatalyst (Fe/NC-S3) efficiently degraded methylene blue, crystal violet, and congo red dyes with removal efficiencies of 98 %, 96 %, and 62 %, respectively, in 30 minutes. They deduced that the nanocatalyst exhibited excellent reusability and practical efficacy in treating textile effluents, maintaining efficiency over multiple reuse cycles. They concluded that SBP biomass can be transformed into advanced, stable, and sustainable nanocatalysts for environmental remediation applications. Similarly, in a study by Soemphol et al. (2020), bacterial cellulose (BC) was combined with silica nanoparticles

derived from rice husks to create BC-silica composite aerogels (CAs) using a sol-gel method. The addition of varying amounts of silica nanoparticles (3–12 % w/v) improved the thermal stability of BC, with the decomposition temperature reaching up to 550°C. SEM, XRD, and FTIR analyses confirmed the presence of silica, and enhanced material properties, providing an economical and eco-friendly method for producing BC-silica CAs with various applications. Also, Nang An et al. (2020), isolated cellulose nanocrystals (CNCs) with high crystallinity from Vietnamese agricultural wastes (Nypa fruticans trunk, coconut husk fibre, and rice husk) using a three-step chemical process. The CNCs exhibited high aspect ratios (200–500 nm in length, 10–15 nm in width) and a crystalline index of nearly 80 %. Characterization techniques confirmed the removal of lignin and improved thermal stability, highlighting the CNCs' potential for diverse applications.

Future developments could focus on expanding the sources of nanocellulose to include a broader array of agricultural residues, such as sugarcane bagasse, wheat straw, and corn stover, thus increasing supply and lowering production costs. Additionally, research could target the enhancement of nanocellulose's mechanical and barrier properties through innovative chemical treatments and hybrid nanomaterials, making it suitable for a wider range of packaging and biomedical applications. Nanocellulose composites, reinforced with other biopolymers or inorganic nanomaterials, could see broader applications in sustainable construction, food packaging, and biomedicine. In the field of regenerative medicine, ongoing studies might explore nanocellulose scaffolds for advanced tissue engineering, due to its natural biocompatibility and strength. Such advances would extend nanocellulose's applications and its appeal as a viable replacement for non-renewable materials.

4.1.6. Nanotechnology in food preservation and nutraceuticals

Agricultural waste is rich in bioactive compounds, which can be refined into nutraceuticals or incorporated into food preservation technology via nanotechnology (Bala et al., 2023).

- **Nutraceuticals:** Waste-derived by-products rich in antioxidants and vitamins can be encapsulated into nanoscale formulations, enhancing their bioavailability and stability, with potential benefits in disease (Ivanović et al., 2023).
- **Nanocoatings for food preservation:** Edible nanocoatings derived from agricultural waste provide barriers against spoilage by moisture and gases, while also offering antimicrobial properties (Poonia and Mishra, 2022).

One of the studies evaluated the antifungal efficacy of ethanolic extracts from mango peels and seeds, and their incorporation into chitosan-based nanocoatings. The nanocoatings, particularly chitosan-peel extract nanoparticles (CPNP), showed significant antifungal activity, completely inhibiting several postharvest phytopathogens. The CPNP reduced infection by 50 % in cv. Kent, while chitosan-seed extract nanoparticles (CSNP) achieved the lowest disease incidence (20 %) in cv. Manila. These findings suggest that mango residue-based nanocoatings are promising natural antifungal agents (Istúriz-Zapata et al., 2022). Similarly, an edible nanocoating was developed using a bio-nano hybrid based on guava extract intercalated with copper oxide nanoparticles, synthesized via a chemical reduction method. The nanocoating significantly improved the thermal stability and reduced the weight loss of the coated material. Applied to fresh papaya, the nanocoating effectively prolonged shelf life by preventing moisture loss and maintaining quality attributes such as pH, acidity, and sensory properties over 18 days. These findings highlight the potential of copper nanohybrid coatings in food preservation (Sharma et al., 2024). Ghosh et al. (2021) developed curcumin-loaded chitosan/iron-functionalized cellulose nanofiber (mgCNF) edible coating for perishable cut fruit, enhancing anti-cancer, physicochemical, and thermal properties. The coating exhibited significant anti-cancer activity against HeLa cells,

reducing cell viability to ~17 % with curcumin. Elemental analysis revealed the material's composition and the iron content were within WHO guidelines. The thermal stability of the materials supports their use for heat-sensitive food items.

Food contaminants, including pesticide residues, heavy metals, and microbial pathogens, pose significant risks to human health and food safety. Among these, pesticide residues are a major concern due to their widespread use in agriculture to protect crops from pests and diseases. However, improper use or overuse of pesticides can lead to harmful residues in food products, requiring efficient detection methods to ensure safe consumption. Silver and gold nanoparticles (AgNPs and AuNPs) have shown great promise in addressing this challenge by providing rapid, sensitive, and cost-effective solutions for monitoring pesticide residues, as well as other food contaminants, in agricultural produce. Silver nanoparticles (AgNPs) are increasingly recognized for their potential in pesticide detection, offering a rapid, sensitive, and cost-effective approach to ensuring food safety. These nanoparticles are versatile in synthesis and application, with agro-residues emerging as sustainable sources for their production. For instance, Das et al., (2021) demonstrated the green synthesis of AgNPs using extracts from the outer shell fiber of *Cocos nucifera* L. fruit, underscoring the role of agricultural by-products in creating value-added nanomaterials. AgNPs have proven highly effective in detecting pesticide residues, addressing the critical need for rapid and reliable monitoring tools in agriculture. Sun et al. (2024b) further utilized borohydride-reduced silver nanoparticles for high-throughput detection of pesticides in fruits and vegetables, achieving exceptional sensitivity and enabling the identification of trace amounts of harmful residues. Such advancements are vital for minimizing health risks and ensuring regulatory compliance in the food industry.

Similarly, gold nanoparticles (AuNPs) have emerged as powerful tools for pesticide detection, particularly through dual-mode sensing systems that integrate fluorescence and colorimetric approaches. Interestingly, agro-waste has also been leveraged as a sustainable resource for synthesizing AuNPs, showcasing their eco-friendly production from a variety of sources. For instance, Yu et al., (2021) demonstrated the efficacy of AuNP-based systems in detecting organophosphorus pesticides, including dichlorvos, trichlorfon, and paraoxon, in agro-products such as pears and Chinese cabbage. Fluorescence assays exhibited remarkable sensitivity, with detection limits as low as 0.0032 ppm for dichlorvos, 0.0096 ppm for trichlorfon, and 0.0074 ppm for paraoxon. Complementarily, colorimetric assays provided reliable detection, with limits of 0.0120 ppm, 0.0224 ppm, and 0.0106 ppm for the respective pesticides. This dual-mode approach not only highlights the versatility and reliability of AuNPs for real-time monitoring of pesticide residues but also underscores the value of agro-waste valorization in advancing sustainable agricultural practices.

Research in this area could delve into creating novel, multifunctional nanocoatings that combine antimicrobial, moisture-barrier, and UV-blocking properties for even more robust food preservation solutions. These advanced coatings, derived from agricultural waste-based nanomaterials, could prolong food shelf life without the need for refrigeration, making them particularly valuable in regions with limited access to cold storage. Additionally, nano-encapsulation techniques for nutraceuticals extracted from agricultural by-products could be further refined to allow for controlled, targeted release of bioactive compounds, enhancing their health benefits and stability over time. This approach could lead to the development of fortified foods or supplements with improved bioavailability, providing a sustainable source of nutrients from otherwise discarded agricultural materials. By focusing on both preservation and health benefits, nanotechnology could revolutionize food systems, reduce food waste, and support better nutrition outcomes on a global scale.

Nanotechnology offers transformative potential for upcycling agricultural waste into high-value products, contributing to a circular economy and addressing environmental challenges. Table 2 highlights

Table 2

Nanomaterials used in the upcycling of agricultural waste into high-value products.

S. No.	Source of Agricultural-waste	Nanomaterials	Value added product /Application of nanomaterials	References
1.	Oil palm waste	Cellulose nanofibers	The production of bio aerogel scaffolds; Food packaging material	(Das et al., 2023; Yahya et al., 2023a)
2.	<i>Musa paradisiaca</i> banana peels	Pectin nanoparticles	Enhancing agents for seed germination and seedling growth	(Arias et al., 2021; Li et al., 2022)
3.	Sawn timber	Nanocellulose	Production of bio-composite membranes; Enhanced-Efficiency Fertilizers (EEFs); Controlled Release Formulations (CRFs) of Pesticides	(Peña-Ortiz et al., 2023; Zaki et al., 2022)
4.	Potato peel	Cellulose nanoparticles	Smart packaging material	(Ramesh and Radhakrishnan, 2019)
5.	Groundnut shell	Carbon nanoparticles	Development of nano fertilizers and nano pesticides; Pollution remediation; Energy storage	(Farmand et al., 2022; Yallappa et al., 2017)
6.	Oil palm waste	Cellulose nanofibers	Antimicrobial agent against <i>S. aureus</i> , <i>E. coli</i>	(Yahya et al., 2023b)
7.	Groundnut shell	Zinc oxide (ZnO), Carbon Dot and ZnO-Carbon Dot Nanocomposite	Antibiotics against <i>B. subtilis</i> , <i>S. aureus</i> , <i>Chromobacterium violaceum</i> , <i>E. coli</i>	(Akpeji et al., 2024)
8.	<i>Salicornia ramosissima</i>	Cellulose nanofibers	Strengthening material.	(Lima et al., 2022)
9.	Potato peel	Cellulose nanoparticles	Antibiotics against <i>S. aureus</i> (strain NCTC 8325), <i>S. flexneri</i> (ATCC 29903), <i>E. coli</i> (strain K12), and <i>S. typhi</i> (strain LT2/SGSC 1412/ATCC 700720)	(Ramesh and Radhakrishnan, 2019)
10.	Black mulberry fruit pulp	Black mulberry encapsulated carboxymethyl cellulose/silica nanoparticles	Antibiotics against <i>Staphylococcus aureus</i> , <i>Escherichia coli</i>	(Sharifi and Pirs, 2021)
11.	Rice husks	Graphene quantum dots	Nano biosorbent	(Mahmoud et al., 2020)
12.	Jackfruit skin	Poly(lactic acid)/jackfruit skin composites	Antimicrobial activity against <i>Staphylococcus aureus</i>	(Zabidi et al., 2023)
13.	Sugarcane Bagasse	Graphene oxide NPs; Carbon quantum dots	Plant growth promoters Seed priming agents	(Baweja and Jeet, 2019; Farhangi-Abri et al., 2024; Maholiya et al., 2023)

(continued on next page)

Table 2 (continued)

S. No.	Source of Agricultural waste	Nanomaterials	Value added product /Application of nanomaterials	References
14.	Orange peels, sugarcane bagasse, Rice bran	Graphene oxide NPs	Soil remediation Strong antimicrobial agents	(Bytešniková et al., 2022; Hashmi et al., 2020; Yan et al., 2024)
15.	Corn cob, Sugarcane bagasse	Silica nanoparticles	Strong anti-fungal agents against <i>Fusarium oxysporum</i> and <i>Aspergillus niger</i>	(Goswami and Mathur, 2022)
16.	Rice husk	Mesoporous silica nanoparticles, Nanosilica	Drought stress mitigating agents; Targeted and imaging in cancer drug delivery	(Bekkam and Thiagarajan, 2024; Chen et al., 2024; S. Yuan et al., 2024)
17.	Red onion peels, kepok banana peels, banana leaves	Nanocellulose	Wound healing, tissue regeneration	(Datta et al., 2024; Manurung et al., 2024)
18.	Cow-dung; Pomegranate peels (PG)	Zinc oxide nanoparticles	UV-protectant; Photocatalyst in waste water treatment	(Shubha et al., 2022; Verbič et al., 2022)
19.	Tea wastes	Magnesium oxide nanoparticles	Adsorbent in industrial wastewater	(Chu et al., 2023)
20.	Coffee wastes	Silver nanoparticles	Removal of photocatalytic, phenol compound, and production of functional nanodevices	(El-Desouky et al., 2023)
21.	Household Green tea waste	Iron nanoparticles	Remediation purposes and degrading chlorinated volatile organic compounds (VOC)	(Rónavári et al., 2023)
22.	Corn cob waste	Maghemite nanoparticles ($\gamma\text{-Fe}_3\text{O}_4$)	Removal of lead pb (II) and cadmium cd (II) ions from aqueous solutions.	(Arul et al., 2023)
23.	Corn cob ash	Copper oxide (CuO) nanoparticles (NPs)	Photocatalytic hydrogen production	(Torres-Arellano et al., 2023)
24.	<i>Prosopis juliflora</i>	Silver-Grey Magnesium alloy-based nanocomposite	Stronger light-weight nano reinforcements for automotive and aviation industries	(Arundeeep and Yuvaraj, 2024)
25.	Garlic husk	Copper nanoparticles (Cu NPs)	Nanomedicine as an antibacterial drug against <i>Escherichia coli</i> , <i>Vibrio cholera</i> , <i>Bacillus cereus</i> , <i>Staphylococcus aureus</i> .	(Senthilkumar et al., 2024)
26.	Rice husks, oat husks and oat straw	Silicon carbide nanostructures	Efficient co-electrocatalysts for water splitting	(Nikitin et al., 2024)

the diverse role of nanomaterials in upcycling agricultural waste into high-value products. By converting residues into biofuels, nano-fertilizers, targeted pesticides, biochar, nanocellulose, and sustainable food packaging, nanotechnology enables efficient resource utilization and reduces reliance on non-renewable resources. This approach not only minimizes waste but also enhances agricultural productivity and fosters economic growth.

Key advancements include nanofertilizers that improve nutrient delivery, nano-based pesticides that reduce chemical usage, biochar for water purification, and nanocellulose for biodegradable packaging. Looking ahead, researchers aim to make these solutions easier to scale up and apply in real-world settings. As these technologies develop, nanotechnology could play a vital role in converting agricultural waste into valuable resources, supporting environmental sustainability and promoting economic growth.

5. Interdisciplinary innovation in transforming agricultural waste into sustainable nanomaterials

The convergence of nanotechnology, biotechnology, and green chemistry is driving transformative solutions for sustainability, particularly in the context of agricultural waste repurposing (Islam and Miyazaki, 2007; Soares et al., 2024). By integrating diverse scientific disciplines, researchers are developing novel, sustainable nanomaterials with significant potential to address pressing environmental and economic challenges.

- Biotechnology meets nanotechnology:** The fusion of biotechnology and nanotechnology is increasingly recognized as a powerful approach for converting agricultural waste into nanomaterials through microbial fermentation and enzymatic processes. Microorganisms such as bacteria and fungi, alongside specialized enzymes, can decompose complex agricultural biomass, such as crop residues, into simple monomers that are ideal for synthesizing valuable nanostructures like nanocellulose, nanochitin, and nanomaterials with unique properties. These biological methods, which operate under mild conditions, reduce the need for toxic chemicals and energy-intensive techniques, thus offering an environmentally friendly and cost-effective alternative to traditional nanomaterial production. Moreover, the resulting nanomaterials, being both renewable and biodegradable, are increasingly finding applications in sectors like packaging, healthcare, and water treatment, where sustainability is key (Hassan and Siddiqui, 2024).
- Green chemistry and nanomaterial synthesis:** Green chemistry plays an indispensable role in enhancing the sustainability of nanomaterial production from agricultural waste. Researchers are turning to green chemistry principles to minimize the environmental impact of nanomaterial synthesis, which typically involves hazardous chemicals and energy-intensive processes (de Oliveira et al., 2024). Utilizing non-toxic solvents, renewable feedstocks, and energy-efficient approaches, such as ionic liquids or water-based systems, researchers are improving the synthesis of nanoparticles while reducing the release of harmful by-products into the environment (Keshu et al., 2021). This innovative shift is transforming the fabrication of nanomaterials into a cleaner, more sustainable process, ensuring the safety of both human health and ecosystems. Applications for these environmentally conscious nanomaterials include bioplastics, energy-efficient coatings, and advanced energy storage devices, which are being developed with reduced ecological footprints (Gilbertson et al., 2015; Gómez-López et al., 2020).
- Hybrid approaches for multifunctional materials:** Hybrid approaches that combine organic biopolymers derived from agricultural byproducts with inorganic nanomaterials are creating multifunctional composites with enhanced properties. For example, agricultural waste such as crop stalks, husks, and peels can be converted into biopolymers like pullulan, chitosan, and cellulose, which

act as renewable matrices for hybrid nanocomposites. These hybrid materials can be tailored to exhibit desirable characteristics, such as mechanical strength, biodegradability, and antimicrobial activity, expanding their potential for diverse applications (Mallakpour et al., 2021). The integration of these organic components with inorganic nanomaterials enables the creation of novel materials with customized properties that can address specific functional requirements, opening new avenues for their use in industries ranging from environmental monitoring and food packaging to energy storage and biomedical applications (Idumah and Hassan, 2016; Nicole et al., 2014; Vodyashkin et al., 2022).

The interdisciplinary synergy between nanotechnology, biotechnology, and green chemistry is facilitating the development of high-performance, eco-friendly materials that transform agricultural waste into valuable resources. This holistic approach is crucial for advancing the circular economy, where waste is reimagined as a resource, helping to mitigate global dependence on non-renewable resources. Furthermore, the hybrid materials developed through this methodology show great promise for addressing environmental and economic challenges across multiple industries, including electronics, biomedicine, and food packaging. By fostering cross-disciplinary collaboration, these innovations are poised to drive sustainable technological advancements that not only offer practical solutions for waste management but also create a pathway to a greener, more sustainable future.

6. Economic and environmental advantages of nanotechnology in waste transformation

Nanotechnology offers a transformative approach to waste valorization, converting agricultural waste into high-value products while providing substantial economic and environmental benefits.

- **Waste valorization:** Nanotechnology allows for the conversion of agricultural waste, previously viewed as a problematic by-product, into valuable resources for emerging industries. This transformation reduces the overall waste and creates renewable materials that can be used in a variety of applications, such as bioplastics, biofuels, and other sustainable products, thus promoting the principles of a circular economy.
- **Minimized environmental footprint:** By turning waste into beneficial materials, nanotechnology reduces the reliance on landfills and open burning, leading to decreased greenhouse gas emissions, soil degradation, and air pollution. This helps mitigate the environmental impact of agricultural waste disposal and promotes cleaner, greener practices.
- **Economic prospects:** Nanotechnology opens up new market opportunities, especially in high-demand sectors such as energy, healthcare, packaging, and sustainable agriculture. This catalyzes job creation, drives innovation, and stimulates economic growth, particularly in rural areas where agricultural waste is abundant.
- **Revenue generation:** By transforming agricultural waste into value-added products, farmers and businesses can tap into new revenue streams, enhancing profitability. Commercializing products like biofuels, bioplastics, and animal feed provides access to global markets and improves the economic viability of agricultural enterprises.
- **Job creation:** The establishment of industries focused on waste processing can create numerous job opportunities in rural regions. Sectors like bioenergy production, biopolymer manufacturing, and waste management would benefit from workforce expansion, contributing to local economic growth.
- **Cost savings:** Nanotechnology reduces waste management costs, including transportation and landfill fees. By processing agricultural waste on-site or selling it to processing facilities, farmers can minimize expenses and maximize profitability.

- **Sustainable economic growth:** Through waste conversion into value-added products, nanotechnology promotes a circular economy where resources are continuously recycled and reused. This approach aligns with global sustainability goals, encouraging long-term economic growth while minimizing environmental degradation.

Nanotechnology provides a sophisticated, eco-friendly framework for transforming agricultural waste into sustainable, high-performance products. It drives both environmental sustainability and economic growth, positioning itself as a key player in the transition towards a circular economy.

7. Challenges and limitations of using nanotechnology to transform agricultural waste into value-added goods

While nanotechnology holds great promise for converting agricultural waste into valuable products, still several challenges and limitations must be addressed to fully realize its potential. These hurdles span technical, regulatory, and market dimensions, each requiring innovative solutions for widespread adoption.

7.1. Technical Barriers

- **Scaling up nanotechnological processes:** One of the primary obstacles to the commercial use of nanotechnology is scaling up from lab-scale processes to industrial-scale production. Many methods for converting agricultural waste into nanomaterials are successful on a small scale but face challenges in terms of energy consumption, equipment requirements, and cost-effectiveness at larger scales (Fernandes et al., 2023).
- **Diversity of biomass feedstock:** Agricultural waste is highly heterogeneous, with different types of biomasses possessing varied chemical properties. This diversity presents a significant challenge for developing standardized processes that can efficiently convert a wide range of agricultural residues into high-quality nanomaterials. As a notable example, Shahi et al. (2021) developed an integrated system for fractionating various agricultural wastes, such as sugarcane bagasse, rice husk, and peanut shells, into biopolymers and silica nanoparticles. The nanoparticles exhibited varying characteristics based on the raw material; those derived from sugarcane bagasse and peanut shells were crystalline, while those from rice husk were amorphous. Additionally, differences in morphology, size, and shape were observed (Shahi et al., 2021).
- **Synthesis of nanomaterials:** Producing nanomaterials with controlled characteristics, such as size, shape, and surface area, at large scales is a complex task. Variations in nanostructure can significantly impact the performance and consistency of the final product, making precision and uniformity crucial for successful commercialization.
- **Production costs:** The production of nanomaterials from agricultural waste often involves specialized equipment and advanced processing techniques, making it costly. Finding cost-effective production methods is essential for making these technologies viable in price-sensitive markets.

7.2. Regulatory and Safety Considerations

- **Toxicity of nanomaterials:** The safety of nanomaterials, especially those derived from agricultural waste, is a significant concern. Due to their small size and high reactivity, nanoparticles may pose potential risks to human health and the environment. Their ability to interact unpredictably with biological systems raises concerns, particularly in consumer goods and products that might end up in the environment. A study by Vijayakumar et al. (2021) demonstrated that silver nanoparticles (Ce-Ag NPs), synthesized using cellulose, showed

dose-dependent cytotoxicity in human keratinocyte (HaCaT) and breast cancer (MCF-7) cells with IC50 values of 5.4 µg/mL and 4.9 µg/mL, respectively. In plant studies, Ce-Ag NPs impacted wheat seed germination and shoot growth, while having minimal effect on mung beans. These results emphasize the importance of further toxicological studies on eco-friendly synthesized nanomaterials.

- **Limited understanding of long-term effects:** Research on the long-term effects of nanomaterials on human health and ecosystems is still in its early stages. The environmental behavior, degradation, and bioaccumulation of these materials are not fully understood, creating uncertainty about their safety in large-scale production and disposal.
- **Regulatory frameworks:** While nanotechnology has advanced rapidly, regulatory frameworks have struggled to keep pace. Inconsistent regulations across countries and lack of standardized guidelines for the manufacture, use, and disposal of nanomaterials create ambiguity, limiting the potential for broad adoption.
- **Environmental and occupational safety:** Worker exposure to nanoparticles during manufacturing and potential environmental release are major concerns. Regulatory bodies must establish comprehensive safety protocols to mitigate these risks, ensuring that the handling, processing, and disposal of nanomaterials are done safely.

7.3. Overcoming Challenges

To overcome these challenges and unlock the full potential of nanotechnology, several strategies can be employed:

- **Investment in research and development:** Ongoing research is essential to develop scalable, cost-effective processes for nanomaterial production. Innovations in energy-efficient production methods, process automation, and catalytic nanomaterials will be key to reducing costs and improving efficiency.
- **Regulatory standardization and safety research:** Governments must create clear, uniform regulations for nanomaterials, ensuring consistency across regions. Further research into the environmental and health impacts of nanomaterials is necessary to instill confidence in their safety.
- **Public education and awareness campaigns:** Public trust is crucial for the widespread adoption of nanotechnology. Transparent communication regarding the benefits, safety, and sustainability of nanoproducts will help shift public perception and increase market acceptance.
- **Market incentives:** Financial incentives, such as tax breaks or subsidies, can encourage businesses to invest in nanotechnology-based waste conversion. These incentives can help offset initial high costs and make the transition to nanotechnology more attractive.

By addressing these challenges, nanotechnology can effectively contribute to the sustainable transformation of agricultural waste, offering economic, environmental, and societal benefits.

8. Future directions and research opportunities for nanotechnology in a circular economy

Future advancements in nanotechnology for a circular economy are focusing on refining and expanding the conversion of agricultural waste into high-value, sustainable nanomaterials. Key areas of research include the development of innovative nanocatalysts, biodegradable nanocomposites, and eco-friendly synthesis methods, which promise more efficient waste transformation processes with potential applications across sectors such as biofuel production, energy storage, and precision agriculture.

One primary research goal is achieving greater control over the physical and chemical properties of nanomaterials such as particle size,

morphology, and surface characteristics to enhance functionality and fit specific application needs. For example, fine-tuning fiber length and crystallinity in nanocellulose production can yield materials with desirable mechanical strength, water resistance, and barrier properties, which are critical for packaging and biocomposites. Similarly, nano-chitin produced from agricultural residues demonstrates unique anti-microbial properties, expanding its potential in fields such as healthcare and food preservation.

Scalability also remains a crucial target, and researchers are focusing on energy-efficient, automated production techniques that make the large-scale manufacturing of nanomaterials more viable. Green synthesis approaches, such as hydrothermal processes and microwave-assisted synthesis, offer promising routes for producing nanomaterials like carbon nanodots and nanofibers at high yields and under environmentally friendly conditions. These carbon-based nanomaterials show potential for energy storage and environmental applications, such as wastewater treatment and soil health monitoring.

Standardization is another priority, as it ensures that nanomaterials derived from diverse agricultural waste sources maintain consistent quality and performance across applications. By establishing reproducible production protocols, researchers can help stabilize nanoproduct markets and support wider adoption across industries. For example, optimized nanocatalysts in biofuel production can accelerate reactions at lower temperatures, reducing energy costs and improving economic feasibility at scale.

These innovations rely on interdisciplinary approaches that integrate materials science, biotechnology, and green chemistry. Collaborative research across these fields is critical for advancing waste upcycling into high-performance, environmentally friendly nanomaterials that contribute to a sustainable circular economy. Ultimately, these advances enable agricultural waste to be reimagined as a valuable resource, offering novel, high-quality materials for diverse industries and reinforcing the global shift towards sustainable production and resource efficiency.

9. Conclusions

Nanotechnology offers a transformative path for redefining agricultural waste, elevating it from an environmental burden to a valuable resource at the forefront of sustainable innovation. By harnessing nanocatalysts, biodegradable nanocomposites, and green chemistry, agricultural residues are being upcycled into products with vast applications from biofuels and nanofertilizers to bioplastics and advanced energy storage solutions. This not only mitigates waste but generates economic opportunities across industries, unlocking new revenue streams and reinforcing the circular economy. The potential of nanotechnology to convert discarded materials into high-performance, eco-friendly products marks a critical step towards sustainable growth. Embracing this approach not only conserves resources but also champions a future where agricultural waste is a cornerstone of both economic and environmental resilience, underscoring nanotechnology's pivotal role in a sustainable, resource-efficient world.

CRediT authorship contribution statement

Shreshtha Saxena: Writing – original draft. **M.P. Moharil:** Writing – review & editing, Supervision. **P.V. Jadhav:** Writing – review & editing, Conceptualization. **Balkrushna Ghodake:** Writing – original draft. **Rupesh Deshmukh:** Writing – review & editing. **Avinash P. Ingle:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of Competing Interest

Authors do not have any conflict of interest to declare.

Data availability

No data was used for the research described in the article.

References

- Adelabu, B.A., Kareem, S.O., Oluwafemi, F., Abideen Adeogun, I., 2019. Bioconversion of corn straw to ethanol by cellulolytic yeasts immobilized in *Mucuna urens* matrix. *J. King Saud. Univ. Sci.* 31, 136–141. <https://doi.org/10.1016/J.JKSUS.2017.07.005>.
- Akhtar, N., Goyal, D., Goyal, A., 2017. Characterization of microwave-alkali-acid pre-treated rice straw for optimization of ethanol production via simultaneous saccharification and fermentation (SSF). *Energy Convers. Manag.* 141, 133–144. <https://doi.org/10.1016/J.ENCONMAN.2016.06.081>.
- Akinbile, C.O., Erazua, A.E., Babalola, T.E., Ajibade, F.O., 2016. Environmental implications of animal wastes pollution on agricultural soil and water quality. *Orig. Pap. Soil Water Res* 11, 172–180. <https://doi.org/10.17221/29/2015-SWR>.
- Akpeji, B.H., Emegha, M.C., Onyenue, E.E., Meshack, O.Q., Elemike, E.E., 2024. Synthesis and characterization of nanoparticles of zinc, carbon dot and zinc-carbon dot nanocomposite from groundnut shell wastes. *J. Appl. Sci. Environ. Manag.* 28, 1771–1780. <https://doi.org/10.4314/JASEM.V28I6.16>.
- Alengbaw, A., Ran, Y., Ghimire, N., Osman, A.I., Ai, P., 2023. Rice straw for energy and value-added products in China: a review, 2023 21:5 21 *Environ. Chem. Lett.* 2729–2760. <https://doi.org/10.1007/S10311-023-01612-3>.
- Amin, M.A., Shukor, H., Shoparwe, N.F., Makhtar, M.M.Z., Abdul Hamid, A., Rongwong, W., 2024. Medium optimization for biobutanol production from palm kernel cake (pkc) hydrolysate by *Clostridium saccharoperbutylacetonicum* N1-4. *Malays. Appl. Biol.* 53, 67–81. <https://doi.org/10.55230/MABJOURNAL.V53I1.2869>.
- Anokye, K., Mohammed, A.S., Agyemang, P., Agya, B.A., Amuah, E.E.Y., Sodoke, S., 2024. A systematic review of the impacts of open burning and open dumping of waste in Ghana: a way forward for sustainable waste management. *Clean. Waste Syst.* 8, 100152. <https://doi.org/10.1016/J.CLWAS.2024.100152>.
- Ariaeenejad, S., Motamedi, E., Ramezani Tazehabad, M., 2023. Effects of agro-waste resources on characteristics of Fe/nanocellulose hybrids and their applications as novel Fenton-like catalysts in dye removal from wastewater. *Process Saf. Environ. Prot.* 176, 918–933. <https://doi.org/10.1016/J.PSEP.2023.06.046>.
- Arias, D., Rodríguez, J., López, B., Méndez, P., 2021. Evaluation of the physicochemical properties of pectin extracted from *Musa paradisiaca* banana peels at different pH conditions in the formation of nanoparticles. *Heliyon* 7. <https://doi.org/10.1016/J.HELIYON.2021.E06059>.
- Arora, J., Ramawat, K.G., Mérillon, J.-M., 2023. Disposal of Agricultural Waste and Its Effects on the Environment, Production of Useful Metabolites and Energy: Potential and Challenges 3–20. https://doi.org/10.1007/978-981-19-8774-8_1.
- Arul, A., Kavitha, S., Anand Babu Christus, A., Surya, V.J., Ravikumar, A., Sivalingam, Y., 2023. Enhanced removal of Pb (II) and Cd (II) ions from aqueous systems using coated magnetic nanoparticles in activated carbon derived from corn cob waste. *Surf. Interfaces* 40, 103095. <https://doi.org/10.1016/J.SURFIN.2023.103095>.
- Arundee, M., Yuvaraj, K.P., 2024. Effect of nanoparticles reinforcement of Silicon dioxide derived from natural agriculture waste *Prosopis juliflora* on Silver-Grey Magnesium nanocomposite: Utilization of silicon dioxide mechanical and tribological properties. <https://doi.org/10.21203/RS.3.RS-4006813/V1>.
- Aydin, M., Koc, P., Sahpaz, K.I., 2023. Investigating the EKC hypothesis with nanotechnology, renewable energy consumption, economic growth and ecological footprint in G7 countries: panel data analyses with structural breaks. *Energy Sources, Part B: Econ., Plan., Policy* 18. <https://doi.org/10.1080/15567249.2022.2163724>.
- Bala, S., Garg, D., Sridhar, K., Inbaraj, B.S., Singh, R., Kamra, S., Tripathi, M., Sharma, M., 2023. Transformation of agro-waste into value-added bioproducts and bioactive compounds: micro/nano formulations and application in the agri-food-pharma sector, 152 10 *Bioengineering* 2023 10, 152. <https://doi.org/10.3390/BIOENGINEERING10020152>.
- Batool, A., Nazir, M., Majeed Zargar, S., 2024. Nano-pesticides and nano-fertilizers from natural (plant/animal) wastes. *Biocatal. Agric. Biotechnol.* 60, 103265. <https://doi.org/10.1016/J.BCAB.2024.103265>.
- Battaglia, M.L., Babaei, S., Sadeghpour, A., Thomason, W.E., Danish, S., Seleiman, M., Ozlu, E., Al-Amery, M., Fike, J.H., Diatta, A.A., 2024. Impact of crop residue removal on crop production, feedstock quality, and theoretical ethanol production in the Mid-Atlantic United States. *Agron. J.* <https://doi.org/10.1002/AGJ2.21659>.
- Baweja, H., Jeet, K., 2019. Economical and green synthesis of graphene and carbon quantum dots from agricultural waste. *Mater. Res Express* 6, 085008. <https://doi.org/10.1088/2053-1591/AB28E5>.
- Behl, T., Kaur, I., Sehgal, A., Singh, S., Sharma, N., Bhatia, S., Al-Harrasi, A., Bungau, S., 2022. The dichotomy of nanotechnology as the cutting edge of agriculture: Nano-farming as an asset versus nanotoxicity. *Chemosphere* 288, 132533. <https://doi.org/10.1016/J.CHEMOSPHERE.2021.132533>.
- Bekkam, R., Thiagarajan, C., 2024. Foliar application of rice husk derived nanosilica for mitigating drought stress in hybrid maize by boosting antioxidant defense system. *J. Hazard. Mater. Adv.* 16, 100482. <https://doi.org/10.1016/J.HAZADV.2024.100482>.
- Bhatia, S.K., Gurav, R., Choi, T.R., Han, Y.H., Park, Y.L., Park, J.Y., Jung, H.R., Yang, S.Y., Song, H.S., Kim, S.H., Choi, K.Y., Yang, Y.K.H., 2019. Bioconversion of barley straw lignin into biodiesel using *Rhodococcus* sp. YHY01. *Bioresour. Technol.* 289, 121704. <https://doi.org/10.1016/J.BIORTECH.2019.121704>.
- Bytešníková, Z., Pečenka, J., Tekielska, D., Kiss, T., Švec, P., Ridošková, A., Bezdička, P., Pekárková, J., Eichmeier, A., Pokluda, R., Adam, V., Richtera, L., 2022. Reduced graphene oxide-based nanometal-composite containing copper and silver nanoparticles protect tomato and pepper against *Xanthomonas euvesicatoria* infection. *Chem. Biol. Technol. Agric.* 9, 1–16. <https://doi.org/10.1186/S40538-022-00347-7/FIGURES/4>.
- Campolo, O., Cherif, A., Ricupero, M., Siscaro, G., Grissa-Lebdi, K., Russo, A., Cucci, L.M., Di Pietro, P., Satriano, C., Desneux, N., Biondi, A., Zappalà, L., Palmeri, V., 2017. Citrus peel essential oil nanoformulations to control the tomato borer, *Tuta absoluta*: Chemical properties and biological activity. *Sci. Rep.* 7. <https://doi.org/10.1038/S41598-017-13413-0>.
- Carota, E., Petruccioli, M., D'Annibale, A., Gallo, A.M., Crognale, S., 2020. Orange peel waste-based liquid medium for biodiesel production by oleaginous yeasts. *Appl. Microbiol. Biotechnol.* 104, 4617–4628. <https://doi.org/10.1007/S00253-020-10579-Y/METRICS>.
- Chauhan, A., Upadhyay, S., Saini, G., Senthilkumar, N., 2022. Agricultural crop residue based biomass in india: potential assessment, methodology and key issues. *Sustain. Energy Technol. Assess.* 53, 102552. <https://doi.org/10.1016/J.SETA.2022.102552>.
- Chen, S.Y., Jian, J.Y., Lin, H.M., 2024. Functionalization of rice husk-derived mesoporous silica nanoparticles for targeted and imaging in cancer drug delivery. *J. Sci. Food Agric.* 104, 2120–2129. <https://doi.org/10.1002/JSCFA.13165>.
- Cheng, C.L., Che, P.Y., Chen, B.Y., Lee, W.J., Lin, C.Y., Chang, J.S., 2012. Biobutanol production from agricultural waste by an acclimated mixed bacterial microflora. *Appl. Energy* 100, 3–9. <https://doi.org/10.1016/J.APENERGY.2012.05.042>.
- Cherwoo, L., Gupta, I., Flora, G., Verma, R., Kapil, M., Arya, S.K., Ravindran, B., Khoo, K.S., Bhatia, S.K., Chang, S.W., Ngamcharussrivichai, C., Ashokkumar, V., 2023. Biofuels an alternative to traditional fossil fuels: a comprehensive review. *Sustain. Energy Technol. Assess.* 60, 103503. <https://doi.org/10.1016/J.SETA.2023.103503>.
- Chu, T.T.H., Tran, T.M.N., Pham, M.T., Viet, N.M., Thi, H.P., 2023. Magnesium oxide nanoparticles modified biochar derived from tea wastes for enhanced adsorption of o-chlorophenol from industrial wastewater. *Chemosphere* 337, 139342. <https://doi.org/10.1016/J.CHEMOSPHERE.2023.139342>.
- Cortés-Peña, Y.R., Woodruff, W., Banerjee, S., Li, Y., Singh, V., Rao, C.V., Guest, J.S., 2024. Integration of plant and microbial oil processing at oilcane biorefineries for more sustainable biofuel production. *GCB Bioenergy* 16, e13183. <https://doi.org/10.1111/GCBB.13183>.
- Dalbanjan, N.P., Eelager, M.P., Korgaonkar, K., Gonal, B.N., Kadapure, A.J., Arakera, S.B., Praveen Kumar, S.K., 2024. Descriptive review on conversion of waste residues into valuable bionanocomposites for a circular bioeconomy. *Nano-Struct. Nano-Objects* 39, 101265. <https://doi.org/10.1016/J.NANOSO.2024.101265>.
- Das, G., Shin, H.S., Kumar, A., Vishnuprasad, C.N., Patra, J.K., 2021. Photo-mediated optimized synthesis of silver nanoparticles using the extracts of outer shell fibre of *Cocos nucifera* L. fruit and detection of its antioxidant, cytotoxicity and antibacterial potential. *Saudi J. Biol. Sci.* 28 (1), 980–987. <https://doi.org/10.1016/J.SJBS.2020.11.022>.
- Das, P., Behera, M.D., Abhilash, P.C., 2024. A rapid assessment of stubble burning and air pollutants from satellite observations. *Trop. Ecol.* 65, 152–157. <https://doi.org/10.1007/S42965-022-00291-5/FIGURES/4>.
- Das, P.P., Kalyani, P., Kumar, R., Khandelwal, M., 2023. Cellulose-based natural nanofibers for fresh produce packaging: current status, sustainability and future outlook. *Sustain. Food Technol.* 1, 528–544. <https://doi.org/10.1039/D3FB00066D>.
- Datta, D., Prajapati, B., Jethva, H., Agrawal, K., Singh, S., Prajapati, B.G., 2024. Value-added nanocellulose valorised from fruit peel waste for potential dermal wound healing and tissue regenerative applications. *Regen. Eng. Transl. Med.* 2024, 1–24. <https://doi.org/10.1007/S40883-024-00348-Y>.
- de Oliveira, M.L., Rodrigues, L.M., Silva da Veiga, M.A.M., Souza, L.R.R., 2024. Advancing nanomaterial synthesis: Harnessing green chemistry for sustainable innovation. *Green Anal. Chem.* 11, 100148. <https://doi.org/10.1016/J.GREEAC.2024.100148>.
- Detchusanand, T., Wiranarongkorn, K., Im-orb, K., 2024. Techno-economic performance analysis of biomass-to-methanol with solid oxide electrolyzer for sustainable bio-methanol production. *Energy* 313, 133764. <https://doi.org/10.1016/J.ENERGY.2024.133764>.
- Devi, Ks, Lakshmi, Vv, 2018. Impacts of nano technology on environment-a review. *Asia Pac. J. Res. ISSN* 2347–4793.
- Divyabharathi, R., Kalidasan, B., Sakthi Suriya, S.S.R., Chinnasamy, S., 2024. Recent advances in sustainable agro residue utilisation, barriers and remediation for environmental management: Present insights and future challenges. *Ind. Crops Prod.* 216, 118790. <https://doi.org/10.1016/J.INDCROP.2024.118790>.
- Duque-Acevedo, M., Belmonte-Ureña, L.J., Cortés-García, F.J., Camacho-Ferre, F., 2020. Agricultural waste: review of the evolution, approaches and perspectives on alternative uses. *Glob. Ecol. Conserv.* 22, e00902. <https://doi.org/10.1016/J.GECCO.2020.E00902>.
- Duque-Acevedo, M., Ulloa-Murillo, L.M., Belmonte-Ureña, L.J., Camacho-Ferre, F., Mercl, F., Tlustoš, P., 2023. Sustainable and circular agro-environmental practices: A review of the management of agricultural waste biomass in Spain and the Czech Republic. *Waste Manag. Res.* 41, 955–969. https://doi.org/10.1177/0734242X221139122/ASSET/IMAGES/LARGE/10.1177_0734242X221139122-FIG6.JPEG.
- Düring, R.-A., Gäch, S., 2002. Utilization of municipal organic wastes in agriculture: where do we stand, where will we go? *J. Plant Nutr. Soil Sci.* 165, 544–556. [https://doi.org/10.1002/1522-2624\(200208\)165:4< 544::AID-JPLN544> 3.0.CO;2-#](https://doi.org/10.1002/1522-2624(200208)165:4< 544::AID-JPLN544> 3.0.CO;2-#).
- El-Desouky, N., Shouei, K., El-Mehasseb, I., El-Kemary, M., 2023. Synthesis of silver nanoparticles using bio valorization coffee waste extract: photocatalytic flow-rate performance, antibacterial activity, and electrochemical investigation. *Biomass--..*

- Convers. Biorefin 13, 15871–15885. <https://doi.org/10.1007/S13399-021-02256-5/TABLES/7>.
- Eskenazi, B., Gunier, R.B., Rauch, S., Kogut, K., Perito, E.R., Mendez, X., Limbach, C., Holland, N., Bradman, A., Harley, K.G., Mills, P.J., Mora, A.M., 2023. Association of lifetime exposure to glyphosate and aminomethylphosphonic acid (AMPA) with liver inflammation and metabolic syndrome at young adulthood: findings from the CHAMACOS study. *Environ. Health Perspect.* 131. <https://doi.org/10.1289/EHP11721>.
- Fahma, F., Febiyanti, I., Lisdaryana, N., Arnata, I., Sartika, D., Sumatera, T., Terusan Ryacudu, J., Hui Jati Agung, W., Selatan, L., 2021. Nanocellulose as a new sustainable material for various applications: a review. *Arch. Mater. Sci. Eng.* 109, 49–64. <https://doi.org/10.5604/01.3001.0015.2624>.
- Farhangi-Abri, S., Ghassemi-Golezani, K., Torabian, S., Rahimzadeh, S., Osati, F., Safarpour, H., 2024. Response of soybean plants to the foliar application of carbon quantum dots under drought stress: a field study. *J. Plant Growth Regul.* 1–11. <https://doi.org/10.1007/S00344-024-11464-Y/FIGURES/2>.
- Farmand, M., Jahanpeyma, F., Gholaminejad, A., Azimzadeh, M., Malaei, F., Shoaie, N., 2022. Carbon nanostructures: a comprehensive review of potential applications and toxic effects, 12 3 *Biotech* 2022 12 (8), 1–48. <https://doi.org/10.1007/S13205-022-03175-6>.
- Feizi, H., Kamali, M., Jafari, L., Rezvani Moghaddam, P., 2013. Phytotoxicity and stimulatory impacts of nanosized and bulk titanium dioxide on fennel (*Foeniculum vulgare* Mill). *Chemosphere* 91, 506–511. <https://doi.org/10.1016/J.CHEMOSPHERE.2012.12.012>.
- Fernandes, C., Jathar, M., Sawant, B.K.S., Warde, T., 2023. Scale-Up of Nanoparticle Manufacturing Process 173–203. https://doi.org/10.1007/978-3-031-31380-6_12.
- Ferreira, F.V., Lona, L.M.F., Pinheiro, I.F., de Souza, S.F., Mei, L.H.I., 2019. Polymer composites reinforced with natural fibers and nanocellulose in the automotive industry: a short review, 2019, Vol. 3, 51 3 *J. Compos. Sci.* 51. <https://doi.org/10.3390/JCS3020051>.
- Fu, X., Zheng, Z., Sha, Z., Cao, H., Yuan, Q., Yu, H., Li, Q., 2022. Biorefining waste into nanobiotechnologies can revolutionize sustainable agriculture. *Trends Biotechnol.* 40, 1503–1518. <https://doi.org/10.1016/J.TIBTECH.2022.09.013/ASSET/577E79B3-7555-4A8C-8956-3371A3B3DE8/MAIN.ASSETS/GR3.JPG>.
- Gaikwad, S., Ingle, A.P., da Silva, S.S., Rai, M., 2018. Immobilized nanoparticles-mediated enzymatic hydrolysis of cellulose for clean sugar production: a novel approach. *Curr. Nanosci.* 15, 296–303. <https://doi.org/10.2174/1573413714666180611081759>.
- Ghosh, T., Nakano, K., Mulchandani, N., Katiyar, V., 2021. Curcumin loaded iron functionalized biopolymeric nanofiber reinforced edible nanocoatings for improved shelf life of cut pineapples. *Food Packag Shelf Life* 28, 100658. <https://doi.org/10.1016/J.FPSL.2021.100658>.
- Gilbertson, L.M., Zimmerman, J.B., Plata, D.L., Hutchison, J.E., Anastas, P.T., 2015. Designing nanomaterials to maximize performance and minimize undesirable implications guided by the Principles of Green Chemistry. *Chem. Soc. Rev.* 44, 5758–5777. <https://doi.org/10.1039/C4CS00445K>.
- Gómez-López, P., Puente-Santiago, A., Castro-Beltrán, A., Santos do Nascimento, L.A., Balu, A.M., Luque, R., Alvarado-Beltrán, C.G., 2020. Nanomaterials and catalysis for green chemistry. *Curr. Opin. Green. Sustain Chem.* 24, 48–55. <https://doi.org/10.1016/J.COGLSC.2020.03.001>.
- Gontard, N., Sonesson, U., Birkved, M., Majone, M., Bolzonella, D., Celli, A., Angellier-Coussy, H., Jang, G.W., Verniquest, A., Broeze, J., Schaer, B., Batista, A.P., Sebok, A., 2018. A research challenge vision regarding management of agricultural waste in a circular bio-based economy. *Crit. Rev. Environ. Sci. Technol.* 48, 614–654. <https://doi.org/10.1080/10643389.2018.1471957>.
- Goswami, P., Mathur, J., 2022. Application of agro-waste-mediated silica nanoparticles to sustainable agriculture. *Bioresour. Bioprocess* 9, 1–12. <https://doi.org/10.1186/S40643-022-00496-5/TABLES/1>.
- Halko, S., Vershkov, O., Horák, J., Lezhenkin, O., Boltianska, L., Kucher, A., Suprun, O., Miroschny, O., Nitsenko, V., 2023. Efficiency of combed straw harvesting technology involving straw decomposition in the soil, 655 *Agriculture* 2023 13 (13), 655. <https://doi.org/10.3390/AGRICULTURE13030655>.
- Han, M., Kang, K.E., Kim, Y., Choi, G.W., 2013. High efficiency bioethanol production from barley straw using a continuous pretreatment reactor. *Process Biochem* 48, 488–495. <https://doi.org/10.1016/J.PROCIBIO.2013.01.007>.
- Hashmi, A., Singh, A.K., Jain, B., Singh, A., 2020. Muffle atmosphere promoted fabrication of graphene oxide nanoparticle by agricultural waste. *Fuller., Nanotub. Carbon Nanostruct.* 28, 627–636. <https://doi.org/10.1080/1536383X.2020.1728744>.
- Hassa, W., Fiala, K., Apiraksakorn, J., Leesing, R., 2024. Sugarcane bagasse valorization through integrated process for single cell oil, sulfonated carbon-based catalyst and biodiesel co-production. *Carbon Resour. Convers.*, 100245 <https://doi.org/10.1016/J.CRCON.2024.100245>.
- Hassan, N., Siddiqui, F., 2024. Merging nanotechnology and biotechnology: transforming plant sciences with nanobiotechnological innovations. *Int. J. Appl. Mach. Learn. Comput. Intell.* 14, 1–19.
- Hijosa-Valsero, M., Paniagua-García, A.I., Díez-Antolínez, R., 2017. Biobutanol production from apple pomace: the importance of pretreatment methods on the fermentability of lignocellulosic agro-food wastes. *Appl. Microbiol Biotechnol.* 101, 8041–8052. <https://doi.org/10.1007/S00253-017-8522-Z/METRICS>.
- Hiranobe, C.T., Gomes, A.S., Paiva, F.F.G., Tolosa, G.R., Paim, L.L., Dognani, G., Cardim, G.P., Cardim, H.P., dos Santos, R.J., Cabrera, F.C., 2024. Sugarcane bagasse: challenges and opportunities for waste recycling. *Pages 662-699 Clean. Technol.* 2024 6 (6), 662–699. <https://doi.org/10.3390/CLEANTECHNOL6020035>.
- Hu, T.Q., 2009. Characterization of lignocellulosic materials. *Charact. Lignocellul. Mater.* 1–370. <https://doi.org/10.1002/9781444305425>.
- Idumah, C.I., Hassan, A., 2016. Emerging trends in eco-compliant, synergistic, and hybrid assembling of multifunctional polymeric bionanocomposites. *Rev. Chem. Eng.* 32, 305–361. https://doi.org/10.1515/REVCE-2015-0046/ASSET/GRAPHIC/JREVCE-2015-0046_CV_002.JPG.
- Ingle, A.P., Rathod, J., Pandit, R., da Silva, S.S., Rai, M., 2017. Comparative evaluation of free and immobilized cellulase for enzymatic hydrolysis of lignocellulosic biomass for sustainable bioethanol production. *Cellulose* 24, 5529–5540. <https://doi.org/10.1007/S10570-017-1517-1/METRICS>.
- Ingle, A.P., Chandel, A.K., Philippini, R., Martiniano, S.E., da Silva, S.S., 2020. Advances in nanocatalysts mediated biodiesel production: a critical appraisal, 256 12 *Symmetry* 2020 12, 256. <https://doi.org/10.3390/SYM12020256>.
- Islam, N., Miyazaki, K., 2007. Nanotechnology systems of innovation: investigation of scientific disciplines' fusion trend into nanotech. *Portland Int. Conf. Manag. Eng. Technol.* 2922–2931. <https://doi.org/10.1109/PICMET.2007.4349636>.
- Istúriz-Zapata, M.A., Correa-Pacheco, Z.N., Bautista-Baños, S., Acosta-Rodríguez, J.L., Hernández-López, M., Barrera-Necha, L.L., 2022. Efficacy of extracts of mango residues loaded in chitosan nanoparticles and their nanocoatings on in vitro and in vivo postharvest fungal. *J. Phytopathol.* 170, 661–674. <https://doi.org/10.1111/JPH.13130>.
- Ivanović, N., Ilić, T., Čirić, M.Z., Todorović, V., Djurić, I., Dabetić, N., 2023. Agri-food by-products as a source of sustainable ingredients for the production of functional foods and nutraceuticals. *Arch. Pharm.* 73, 190–204. <https://doi.org/10.5937/ARHFARM73-44481>.
- Joeniarti, E., Susilo, A., Ardiarini, N.R., Indrasari, N., Fahmi, M.Z., 2019. Efficiency study of neem seeds-based nanobiopesticides. *Chem. Chem. Technol.* 13 240–246. <https://doi.org/10.23939/CHCHT13.02.240>.
- Johnravindar, D., Elangovan, N., Gopal, N.O., Muthaiyan, A., Fei, Q., 2021. Biobutanol production from cassava waste residue using *Clostridium* sp. AS3 in batch culture fermentation. *Biofuels* 12, 1259–1266. <https://doi.org/10.1080/17597269.2019.1608671>.
- Jones, S.L., Gibson, K.E., Ricke, S.C., 2021. Critical factors and emerging opportunities in food waste utilization and treatment technologies. *Front Sustain Food Syst.* 5, 781537. <https://doi.org/10.3389/FSUFS.2021.781537/BIBTEX>.
- Joshi, S.M., Waghmare, J.S., Sonawane, K.D., Waghmare, S.R., 2015. Bio-ethanol and bio-butanol production from orange peel waste. *Biofuels* 6, 55–61. <https://doi.org/10.1080/17597269.2015.1045276>.
- Kamboj, R., Ms, D., 2021. Orange peel extract enhanced sugar recovery and butanol production from potato peel by *Clostridium acetobutylicum*. *Int J. Green. Energy* 18, 987–997. <https://doi.org/10.1080/15435075.2021.1890083>.
- Karatay, S.E., Demiray, E., Dönmez, G., 2022. Usage potential of apple and carrot pomaces as raw materials for newly isolated yeast lipid-based biodiesel production. *Biomass-- Convers. Biorefin* 12, 4773–4783. <https://doi.org/10.1007/S13399-020-01174-2/METRICS>.
- Karić, N., Maia, A.S., Teodorović, A., Atanasova, N., Langergraber, G., Crini, G., Ribeiro, A.R.L., Dolić, M., 2022. Bio-waste valorisation: agricultural wastes as biosorbents for removal of (in)organic pollutants in wastewater treatment. *Chem. Eng. J. Adv.* 9, 100239. <https://doi.org/10.1016/J.CEJA.2021.100239>.
- Kasmuri, N.H., Kamarudin, S.K., Abdullah, S.R.S., Hasan, H.A., Som, A.M., 2019. Integrated advanced nonlinear neural network-simulink control system for production of bio-methanol from sugar cane bagasse via pyrolysis. *Energy* 168, 261–272. <https://doi.org/10.1016/J.ENERGY.2018.11.056>.
- Kesari, K.K., Soni, R., Jamal, Q.M.S., Tripathi, P., Lal, J.A., Jha, N.K., Siddiqui, M.H., Kumar, P., Tripathi, V., Ruokolainen, J., 2021. Wastewater treatment and reuse: a review of its applications and health implications. *Water Air Soil Pollut.* 232, 1–28. <https://doi.org/10.1007/S11270-021-05154-8/FIGURES/5>.
- Keshu, Rani, Yadav, M., Meenu, J., Chaudhary, S., Shanker, U., 2021. An updated review on synthetic approaches of green nanomaterials and their application for removal of water pollutants: Current challenges, assessment and future perspectives. *J. Environ. Chem. Eng.* 9, 106763. <https://doi.org/10.1016/J.JECE.2021.106763>.
- Khan, M.N., Sial, T.A., Ali, A., Wahid, F., 2024. Impact of agricultural wastes on environment and possible management strategies 79–108. https://doi.org/10.1007/978-3-031-50503-4_4.
- Kiehadrouinezhad, M., Merabet, A., Hosseinzadeh-Bandbafha, H., 2024. Landfill source of greenhouse gas emission. *Advances and technology development in greenhouse gases: emission, capture and conversion: Greenhouse gases emissions and climate change* 123–145. <https://doi.org/10.1016/B978-0-443-19231-9.00023-5>.
- Kim, S., Kim, C.H., 2013. Bioethanol production using the sequential acid/alkali-pretreated empty palm fruit bunch fiber. *Renew. Energy* 54, 150–155. <https://doi.org/10.1016/J.RENENE.2012.08.032>.
- Koul, B., Yakob, M., Shah, M.P., 2022. Agricultural waste management strategies for environmental sustainability. *Environ. Res* 206, 112285. <https://doi.org/10.1016/J.ENVRES.2021.112285>.
- Kumar, J.A., Sathish, S., Prabu, D., Renita, A.A., Saravanan, A., Deivayanai, V.C., Anish, M., Jayarabakar, J., Baigzenhov, O., Hosseini-Bandegharai, A., 2023. Agricultural waste biomass for sustainable bioenergy production: feedstock, characterization and pre-treatment methodologies. *Chemosphere* 331, 138680. <https://doi.org/10.1016/J.CHEMOSPHERE.2023.138680>.
- Kupnik, K., Primožič, M., Kokol, V., Leitgeb, M., 2020. Nanocellulose in drug delivery and antimicrobially active materials, 2825 12 *Polymers* 2020 12, 2825. <https://doi.org/10.3390/POLYM12122825>.
- Li, R., Li, M., He, J., Xie, H., Wang, W., Zhang, M., Cabrera-Barjas, G., Morganti, P., Yin, H., 2022. Preparation of pectin nanospheres and its effect on wheat (*Triticum aestivum* L.) seed germination and growth. *J. Plant Growth Regul.* 41, 3197–3207. <https://doi.org/10.1007/S00344-021-10505-0/TABLES/2>.

- Li, X., Mupondwa, E., Panigrahi, S., Tabil, L., Sokhansanj, S., Stumborg, M., 2012. A review of agricultural crop residue supply in Canada for cellulosic ethanol production. *Renew. Sustain. Energy Rev.* 16, 2954–2965. <https://doi.org/10.1016/J.RSER.2012.02.013>.
- Lima, A.R., Cristofoli, N.L., Rosa da Costa, A.M., Saraiva, J.A., Vieira, M.C., 2022. Comparative study of the production of cellulose nanofibers from agro-industrial waste streams of *Salicornia maritima* by acid and enzymatic treatment. *Food Bioprod. Process.* 137, 214–225. <https://doi.org/10.1016/J.FBP.2022.11.012>.
- Liscano, J., Wilson, C., Norman, R., Slaton, N., 2000. Zinc availability to rice from seven granular zinc fertilizers.
- Lu, Y., Zhai, Y., Liu, M., Wu, Q., 2010. Biodiesel production from algal oil using cassava (*Manihot esculenta* Crantz) as feedstock. *J. Appl. Phycol.* 22, 573–578. <https://doi.org/10.1007/S10811-009-9496-8/METRICS>.
- Luo, Hao, Zhao, Z.J., Huang, R., Wang, Z.B., Lin, J.Q., Chen, L.X., 2023. High-temperature fermentation of corn stover for biodiesel production using *Candida tropicalis* with enhanced lipid accumulation: a new strategy for breeding thermotolerant biodiesel-production strains. *Ind. Crops Prod.* 206, 117542. <https://doi.org/10.1016/J.INDCROP.2023.117542>.
- Luo, Hongzhen, Shi, Y., Xie, F., Zhou, T., Gao, L., Yang, R., Wang, Z., 2023. Efficient co-production of fermentable sugars and biobutanol from corn stover based on a novel butyric acid pretreatment strategy. *Ind. Crops Prod.* 191, 115976. <https://doi.org/10.1016/J.INDCROP.2022.115976>.
- Mahmoud, M.E., Fekry, N.A., Abdelfattah, A.M., 2020. A novel nanobiosorbent of functionalized graphene quantum dots from rice husk with barium hydroxide for microwave enhanced removal of lead (II) and lanthanum (III). *Bioresour. Technol.* 298. <https://doi.org/10.1016/J.BIORTECH.2019.122514>.
- Maholiya, A., Ranjan, P., Khan, R., Murali, S., Nainwal, R.C., Chauhan, P.S., Sathish, N., Chaurasia, J.P., Srivastava, A.K., 2023. An insight into the role of carbon dots in the agriculture system: a review. *Environ. Sci. Nano* 10, 959–995. <https://doi.org/10.1039/D2EN000954D>.
- Mallakpour, S., Siros, F., Hussain, C.M., 2021. A journey to the world of fascinating ZnO nanocomposites made of chitosan, starch, cellulose, and other biopolymers: Progress in recent achievements in eco-friendly food packaging, biomedical, and water remediation technologies. *Int. J. Biol. Macromol.* 170, 701–716. <https://doi.org/10.1016/J.IJBIOMAC.2020.12.163>.
- Manurung, P., Yakosati, S., Putri, F.N., Suciyati, S.W., 2024. Comparative study of nanocellulose from waste of red onion and kepok banana (*Musa acuminata* x *balbisiana*) peels using acid hydrolysis method. 4th Int. Conf. Appl. Sci., Math., Inform.: ICASMI2022 2970 020007. <https://doi.org/10.1063/5.0209248/3311340>.
- Meena, D., Gautam, C., Patidar, A., Meena, H., Prakash, V., 2017. Nano-fertilizers is a new way to increase nutrients use efficiency in crop production. *Int. J. Agric. Sci.* 9, 3831–3833.
- Mondal, S.H., Chattopadhyay, A.K., 2024. Impact of stubble burning on air pollution and climate change in East Burdwan District, India. *Indian Econ. Rev.* 59, 311–330. <https://doi.org/10.1007/S41775-024-00227-X/METRICS>.
- Morganti, P., 2015. Bionanotechnology & bioeconomy for a greener development. *J. Appl. Cosmetol.* 33, 51–65.
- Morikawa, Y., Zhao, X., Liu, D., 2014. Biological co-production of ethanol and biodiesel from wheat straw: a case of dilute acid pretreatment. *RSC Adv.* 4, 37878–37888. <https://doi.org/10.1039/C4RA007251K>.
- Mujtaba, M., Fernandes Fraceto, L., Fazeli, M., Mukherjee, S., Savassa, S.M., Araujo de Medeiros, G., do Espírito Santo Pereira, A., Mancini, S.D., Lipponen, J., Vilaplana, F., 2023. Lignocellulosic biomass from agricultural waste to the circular economy: a review with focus on biofuels, biocomposites and bioplastics. *J. Clean. Prod.* 402, 136815. <https://doi.org/10.1016/J.JCLEPRO.2023.136815>.
- Mukherjee, A., Majumdar, S., Servin, A.D., Pagano, L., Dhankher, O.P., White, J.C., 2016. Carbon nanomaterials in agriculture: a critical review. *Front Plant Sci.* 7. <https://doi.org/10.3389/FPLS.2016.00172>.
- Nabila, D.S., Chan, R., Syamsuri, R.R.P., Nurlilasari, P., Wan-Mohtar, W.A.Q.I., Ozturk, A.B., Rossiana, N., Doni, F., 2024. Biobutanol production from underutilized substrates using *Clostridium*: Unlocking untapped potential for sustainable energy development. *Curr. Res Micro Sci.* 7, 100250. <https://doi.org/10.1016/J.CRMICR.2024.100250>.
- Nandhini, R., Rameshwar, S.S., Sivaprakash, B., Rajamohan, N., Monisha, R.S., 2023. Carbon neutrality in biobutanol production through microbial fermentation technique from lignocellulosic materials – a biorefinery approach. *J. Clean. Prod.* 413, 137470. <https://doi.org/10.1016/J.JCLEPRO.2023.137470>.
- Nang An, V., Chi Nhan, H.T., Tap, T.D., Van, T.T.T., Van Viet, P., Van Hieu, L., 2020. Extraction of high crystalline nanocellulose from bio renewable sources of Vietnamese agricultural wastes. *J. Polym. Environ.* 28, 1465–1474. <https://doi.org/10.1007/S10924-020-01695-X/METRICS>.
- Nath, P.C., Ojha, A., Debnath, S., Sharma, M., Sridhar, K., Nayak, P.K., Inbaraj, B.S., 2023b. Bioregeneration of valuable nanomaterials from agro-wastes: a comprehensive review, 561 13 *Agronomy* 2023 13, 561. <https://doi.org/10.3390/AGRONOMY13020561>.
- Nath, P.C., Ojha, A., Debnath, S., Sharma, M., Sridhar, K., Nayak, P.K., Inbaraj, B.S., 2023a. Bioregeneration of valuable nanomaterials from agro-wastes: a comprehensive review, 561 13 *Agronomy* 2023 13, 561. <https://doi.org/10.3390/AGRONOMY13020561>.
- Nazeer, A., Ahmad, F., Verma, N., Ahmad, S., 2023. Targeted delivery of nanopesticides. *Nanotechnol. Life Sci. Part F* 1609 125–139. https://doi.org/10.1007/978-3-031-41333-9_8.
- Nazem, M.A., Zare, M.H., Shirazian, S., 2020. Preparation and optimization of activated nano-carbon production using physical activation by water steam from agricultural wastes. *RSC Adv.* 10, 1463–1475. <https://doi.org/10.1039/C9RA07409K>.
- Neri, A., Bernardi, B., Zimbalatti, G., Benalia, S., 2023. An overview of anaerobic digestion of agricultural by-products and food waste for biomethane production, 6851 16 *Energies* 2023 16, 6851. <https://doi.org/10.3390/EN16196851>.
- Nezafat, Z., Dong, Y., Nasrollahzadeh, M., Shafiei, N., Gharoubi, H., Javanshir, S., 2024. Recent progresses in energy conversion and storage of agricultural waste-derived (carbon/nano) materials: A review. *Green. Chem.* <https://doi.org/10.1039/D3GC04332K>.
- Nicole, L., Laberty-Robert, C., Rozes, L., Sanchez, C., 2014. Hybrid materials science: a promised land for the integrative design of multifunctional materials. *Nanoscale* 6, 6267–6292. <https://doi.org/10.1039/C4NR01788A>.
- Nikitin, D.S., Shanenkov, I.I., Yeletsy, P.M., Nassyrbayev, A., Tabakaev, R.B., Shanenkova, Y.L., Ryskulov, D.N., Tsimmerman, A.I., Sivkov, A.A., 2024. Agricultural waste derived silicon carbide composite nanopowders as efficient electrocatalysts for water splitting. *J. Clean. Prod.* 442, 140890. <https://doi.org/10.1016/J.JCLEPRO.2024.140890>.
- Nongbet, A., Mishra, A.K., Mohanta, Y.K., Mahanta, S., Ray, M.K., Khan, M., Baek, K.H., Chakrabarty, I., 2022. Nanofertilizers: A Smart and Sustainable Attribute to Modern Agriculture, 2587 11 *Plants* 2022 11, 2587. <https://doi.org/10.3390/PLANTS11192587>.
- Nurazzi, N.M., Jenol, M.A., Kamarudin, S.H., Aisyah, H.A., Hao, L.C., Yusuff, S.M., Amira, M.R.N., Harussani, M.M., Norrahman, M.N.F., Ilyas, R.A., Norli, A., 2022. Nanocellulose composites in the automotive industry. *Ind. Appl. Nanocellulose Nanocompos.* 439–467. <https://doi.org/10.1016/B978-0-323-89909-3.00011-0>.
- Nweze, J.A., Gupta, S., Akor, J., Nwuche, C.O., Nweze, J.E., Unah, V.U., 2023. Animal waste: an environmentally sustainable management approach. *Clim. Chang. Mitig. Sustain. Bioenergy Harvest Anim. Waste* 1–33. https://doi.org/10.1007/978-3-031-26224-1_1.
- Odubo, T.C., Kosoe, E.A., 2024. Sources of Air Pollutants: Impacts and Solutions 1–47. <https://doi.org/10.1007/978-3-031-11272-7>.
- Onu, P., Mbohwa, C., 2021. Agricultural waste diversity and sustainability issues: Sub-Saharan Africa as a case study. *Agric. Waste Divers. Sustain. Issue.: Sub-Sahar. Afr. a case Study* 1–187. <https://doi.org/10.1016/B978-0-323-85402-3.01001-9>.
- Pandit, G., Tiwar, R.K., Shanvi, Farheen, G., Singh, V., Ahmed, G., Kumar, A., Mishra, V., Singh, M., 2024. Paddy Straw Waste and Its Conversion into Value-Added Products 103–127. https://doi.org/10.1007/978-981-97-1623-4_5.
- Pardo, G., del Prado, A., Martínez-Mena, M., Bustamante, M.A., Martín, J.A.R., Álvaro-Fuentes, J., Moral, R., 2017. Orchard and horticulture systems in Spanish Mediterranean coastal areas: Is there a real possibility to contribute to C sequestration? *Agric. Ecosyst. Environ.* 238, 153–167. <https://doi.org/10.1016/J.AGEE.2016.09.034>.
- Peña-Ortiz, M., Rincón, E., Serrano, L., García, A., 2023. Recent Nanocellulose Applications for Sustainable Agriculture—A Review 185–213. https://doi.org/10.1007/978-981-99-2473-8_8.
- Picot-Allain, M.C.N., Emmambux, M.N., 2023. Isolation, characterization, and application of nanocellulose from agro-industrial by-products: a review. *Food Rev. Int.* 39, 941–969. <https://doi.org/10.1080/87559129.2021.1928689>.
- Poonia, A., Mishra, A., 2022. Edible nanocoatings: potential food applications, challenges and safety regulations. *Nutr. Food Sci.* 52, 497–514. <https://doi.org/10.1108/NFS-07-2021-0222/FULL/XML>.
- Population. United Nations [WWW Document], 2023. URL (<https://www.un.org/en/global-issues/population/>) (accessed 9.28.24).
- Poy Andreu, H., 2024. Development of pretreatment processes with ionic liquids and deep eutectic solvents for the valorization of rice straw into biobutanol.
- Pradhan, P., Sinha, A.K., Pandit, T.K., 2024. The effect of stubble burning and residue management on soil properties: a review. *Int. J. Plant Soil Sci.* 36, 36–49. <https://doi.org/10.9734/IJPSS/2024/V36I64604>.
- Prihatiningtyas, I., Heryadi, E., Ramadhan, R., Purnomo, A., Alfiyya, A., Abdullah, H., 2024. Processing and characterization of oil palm loose fruits as a raw material for biodiesel. *J. Chem. Didact. Acta (J. Chem. Chem. Educ.)* 12, 6–11. <https://doi.org/10.24815/JCD.V12I1.34955>.
- Puglia, D., Pezzolla, D., Gigliotti, G., Torre, L., Bartucca, M.L., Del Buono, D., 2021. The opportunity of valorizing agricultural waste, through its conversion into bio stimulants, biofertilizers, and biopolymers, 2710 13 *Sustainability* 2021 13, 2710. <https://doi.org/10.3390/SU13052710>.
- Ramesh, S., Radhakrishnan, P., 2019. Cellulose nanoparticles from agro-industrial waste for the development of active packaging. *Appl. Surf. Sci.* 484, 1274–1281. <https://doi.org/10.1016/J.APSUSC.2019.04.003>.
- Rana, A.K., Mishra, Y.K., Gupta, V.K., Thakur, V.K., 2021. Sustainable materials in the removal of pesticides from contaminated water: perspective on macro to nanoscale cellulose. *Sci. Total Environ.* 797, 149129. <https://doi.org/10.1016/J.SCTOTENV.2021.149129>.
- Rani, M., Shanker, U., 2017. Degradation of traditional and new emerging pesticides in water by nanomaterials: recent trends and future recommendations, 15:6 15 *Int. J. Environ. Sci. Technol.* 2017 1347–1380. <https://doi.org/10.1007/S13762-017-1512-Y>.
- Raut, M.P., Pandhal, J., Wright, P.C., 2021. Effective pretreatment of lignocellulosic substrates using barley straw-adapted microbial consortia to enhanced biomethanation by anaerobic digestion. *Bioresour. Technol.* 321, 124437. <https://doi.org/10.1016/J.BIORTECH.2020.124437>.
- Redlingshöfer, B., Coudurier, B., Georget, M., 2017. Quantifying food loss during primary production and processing in France. *J. Clean. Prod.* 164, 703–714. <https://doi.org/10.1016/J.JCLEPRO.2017.06.173>.
- Rónavári, A., Balázs, M., Szilágyi, Á., Molnár, C., Kotormán, M., Ilisz, I., Kiricsi, M., Kónya, Z., 2023. Multi-round recycling of green waste for the production of iron nanoparticles: synthesis, characterization, and prospects in remediation. *Discov. Nano* 18, 1–16. <https://doi.org/10.1186/S11671-023-03784-X/FIGURES/5>.

- Ruan, L., Wu, H., Wu, Shiya, Zhou, L., Wu, Shangxin, Shang, C., 2024. Optimizing the conditions of pretreatment and enzymatic hydrolysis of sugarcane bagasse for bioethanol production. *ACS Omega* 9, 29566–29575. <https://doi.org/10.1021/ACSEOMEGA.4C02485/ASSET/IMAGES/LARGE/AO4C02485.0007.JPEG>.
- Saadatinavaz, F., Karimi, K., Denayer, J.F.M., 2021. Hydrothermal pretreatment: An efficient process for improvement of biobutanol, biohydrogen, and biogas production from orange waste via a biorefinery approach. *Bioresour. Technol.* 341, 125834. <https://doi.org/10.1016/j.biortech.2021.125834>.
- Saetiao, P., Kongrit, N., Cheng, C.K., Jitjamnong, J., Direksilp, C., Khantikulanon, N., 2023. Catalytic conversion of palm oil into sustainable biodiesel using rice straw ash supported-calcium oxide as a heterogeneous catalyst: process simulation and techno-economic analysis. *Case Stud. Chem. Environ. Eng.* 8, 100432. <https://doi.org/10.1016/j.csee.2023.100432>.
- Sakthivel, S., Muthusamy, K., Thangarajan, A.P., Thiruvengadam, M., Venkidasamy, B., 2024. Nano-based biofuel production from low-cost lignocellulose biomass: environmental sustainability and economic approach, 2024 47: 47 *Bioprocess Biosyst. Eng.* 971–990. <https://doi.org/10.1007/S00449-024-03005-4>.
- Saxena, S., Ingle, A.P., P. Moharil, M., 2023. Nanobiocatalysts: the promising alternatives for conventional biocatalysts used in lignocellulosic biomass hydrolysis. *Nanotechnol. Biorefinery* 143–162. <https://doi.org/10.1016/B978-0-323-95965-0.00007-X>.
- Senthilkumar, A., Muthuswamy, R., Uma Maheshwari Nallal, Ramaiyan, S., Kannan, P., Muthupandi, S., Lakshminarayanan, S.P., Sambasivam, S., Ayyar, M., 2024. Green synthesis of copper nanoparticles from agro-waste garlic husk. *Z. Phys. Chem.* 238, 75–88. <https://doi.org/10.1515/ZPCH-2023-0291/MACHINEREADABLECITATION/RIS>.
- Shahi, N., Wang, P., Adhikari, S., Min, B., Rangari, V.K., 2021. Biopolymers fractionation and synthesis of nanocellulose/silica nanoparticles from agricultural byproducts. *ACS Sustain. Chem. Eng.* 9, 6284–6295. https://doi.org/10.1021/ACSSUSCHEMENG.0C09342/SUPPL_FILE/SCOC09342_SI_001.PDF.
- Shannugam, H., Raghavan, V., Rajagopal, R., Goyette, B., Lyu, L., Zhou, S., An, C., 2024. Evaluating sustainable practices for managing residue derived from wheat straw, 554 11 *Bioengineering* 2024 11, 554. <https://doi.org/10.3390/BIOENGINEERING11060554>.
- Sharifi, K.A., Pirs, S., 2021. Biodegradable film of black mulberry pulp pectin/chlorophyll of black mulberry leaf encapsulated with carboxymethylcellulose/silica nanoparticles: investigation of physicochemical and antimicrobial properties. *Mater. Chem. Phys.* 267, 124580. <https://doi.org/10.1016/j.MATCHEMPHYS.2021.124580>.
- Sharma, B., Nigam, S., Verma, A., Garg, M., Mittal, A., Sadhu, S.D., 2024. A biogenic approach to develop guava derived edible copper and zinc oxide nanocoating to extend shelf life and efficiency for food preservation. *J. Polym. Environ.* 32, 331–344. <https://doi.org/10.1007/S10924-023-02972-1/METRICS>.
- Sharma, P., Gaur, V.K., Sirohi, R., Varjani, S., Hyoun Kim, S., Wong, J.W.C., 2021. Sustainable processing of food waste for production of bio-based products for circular bioeconomy. *Bioresour. Technol.* 325, 124684. <https://doi.org/10.1016/j.biortech.2021.124684>.
- Sher, F., Ziani, I., Hameed, M., Ali, S., Sulejmanović, J., 2024. Advanced nanomaterials design and synthesis for accelerating sustainable biofuels production – a review. *Curr. Opin. Green. Sustain. Chem.* 47, 100925. <https://doi.org/10.1016/j.COGSC.2024.100925>.
- Shubha, J.P., Kavalli, K., Adil, S.F., Assal, M.E., Hatshan, M.R., Dubasi, N., 2022. Facile green synthesis of semiconducting ZnO nanoparticles for photocatalytic degradation of dyes from the textile industry: a kinetic approach. *J. King Saud. Univ. Sci.* 34, 102047. <https://doi.org/10.1016/j.jksus.2022.102047>.
- Smitha, J.K., Bhaskar, S.P., Jose, A., Geetha, T., 2024. Synthesis of nano calcium borate using sugarcane bagasse extract as a capping agent and its potential to promote germination in cowpea seeds. *Results Chem.* 10, 101722. <https://doi.org/10.1016/j.RECHEM.2024.101722>.
- Soares, C., Dorosh, O., Fernandes, F., Grosso, C., Moreira, M., Delerue-Matos, C., 2024. Biotechnological Approaches for Agriculture Waste Transformation 85–107. https://doi.org/10.1007/978-3-031-61133-9_4.
- Sobczak, A., Chomać-Pierzecka, E., Kokieli, A., Różycka, M., Stasiak, J., Sobon, D., 2022. Economic conditions of using biodegradable waste for biogas production, using the example of Poland and Germany, 5239 15 *Energies* 2022 15, 5239. <https://doi.org/10.3390/EN15145239>.
- Soemphol, W., Charee, P., Audtarat, S., Sompech, S., Hongsachart, P., Dasri, T., 2020. Characterization of a bacterial cellulose-silica nanocomposite prepared from agricultural waste products. *Mater. Res. Express* 7, 015085. <https://doi.org/10.1088/2053-1591/AB6C25>.
- Soliman, M., Shawky, A., Elshepiny, M.A., 2024. Assessing the efficacy of agro-waste biochar-derived nanoparticles for purification of municipal wastewater, agricultural drainage water and industrial effluents. *Egypt. J. Soil Sci.* 64 (3), 885–896. <https://doi.org/10.21608/EJSS.2024.277811.1738>.
- Song, B., Almatrafi, E., Tan, X., Luo, S., Xiong, W., Zhou, C., Qin, M., Liu, Y., Cheng, M., Zeng, G., Gong, J., 2022. Biochar-based agricultural soil management: An application-dependent strategy for contributing to carbon neutrality. *Renew. Sustain. Energy Rev.* 164, 112529. <https://doi.org/10.1016/j.RSER.2022.112529>.
- Souza, P.G.A., do Carmo Lima Carvalho, J., de Souza, L.Z.M., Lima, E.N., de Aguiar, M. G., Lima, R.P., Ferreira, O.E., Pimenta, L.P.S., Machado, A.R.T., 2024. Effect of pyrolysis temperature on the production of biochar and biomethanol from sugarcane bagasse. *Bioenergy Res* 17, 1394–1401. <https://doi.org/10.1007/S12155-024-10733-8/METRICS>.
- Sun, X., Dou, Z., Shurson, G.C., Hu, B., 2024a. Bioprocessing to upcycle agro-industrial and food wastes into high-nutritional value animal feed for sustainable food and agriculture systems. *Resour. Conserv. Recycl.* 201, 107325. <https://doi.org/10.1016/J.RESCONREC.2023.107325>.
- Sun, X., Zhao, Y., Liu, L., Qiao, Y., Yang, C., Wang, X., Li, Q., Li, Y., 2024b. Visual whole-process monitoring of pesticide residues: an environmental perspective using surface-enhanced Raman spectroscopy with dynamic borohydride-reduced silver nanoparticles. *J. Hazard. Mat.* 465, 133338. <https://doi.org/10.1016/J.JHAZMAT.2023.133338>.
- Taghizadeh-Alisaraei, A., Tatari, A., Khanali, M., Keshavarzi, M., 2023. Potential of biofuels production from wheat straw biomass, current achievements and perspectives: a review. *Biofuels* 14, 79–92. <https://doi.org/10.1080/17597269.2022.2118779>.
- Teigerisova, D.A., Hamelin, L., Thomsen, M., 2019. Review of high-value food waste and food residues biorefineries with focus on unavoidable wastes from processing. *Resour. Conserv. Recycl.* 149, 413–426. <https://doi.org/10.1016/J.RESCONREC.2019.05.003>.
- Torres-Arellano, S., Torres-Martinez, L.M., Luévano-Hipólito, E., Aleman-Ramirez, J.L., Sebastian, P.J., 2023. Biologically mediated synthesis of CuO nanoparticles using corn COB (*Zea mays*) ash for photocatalytic hydrogen production. *Mater. Chem. Phys.* 301, 127640. <https://doi.org/10.1016/J.MATCHEMPHYS.2023.127640>.
- Valdez-Vazquez, I., Pérez-Rangel, M., Tapia, A., Buitrón, G., Molina, C., Hernández, G., Amaya-Delgado, L., 2015. Hydrogen and butanol production from native wheat straw by synthetic microbial consortia integrated by species of *Enterococcus* and *Clostridium*. *Fuel* 159, 214–222. <https://doi.org/10.1016/J.FUEL.2015.06.052>.
- Verbić, A., Brenčić, K., Dolenc, M., Primc, G., Recek, N., Šala, M., Gorjanc, M., 2022. Designing UV-protective and hydrophilic or hydrophobic cotton fabrics through in-situ ZnO synthesis using biodegradable waste extracts. *Appl. Surf. Sci.* 599, 153931. <https://doi.org/10.1016/J.APSUSC.2022.153931>.
- Verma, M., Singh, P., Dhanorkar, M., 2024. Sustainability in residue management: a review with special reference to Indian agriculture. *Paddy Water Environ.* 22, 1–15. <https://doi.org/10.1007/S10333-023-00952-8/FIGURES/4>.
- Vijayakumar, S., Chen, J., Amarnath, M., Tungare, K., Bhoir, M., Divya, M., González-Sánchez, Z.I., Durán-Lara, E.F., Vaseeharan, B., 2021. Cytotoxicity, phytotoxicity, and photocatalytic assessment of biopolymer cellulose-mediated silver nanoparticles. *Colloids Surf. A Physicochem. Eng. Asp.* 628, 127270. <https://doi.org/10.1016/J.COLSURFA.2021.127270>.
- Vodyashkin, A.A., Kezimana, P., Vetcher, A.A., Stanishvskiy, Y.M., 2022. Biopolymeric nanoparticles—multifunctional materials of the future, 2287 14 *Polymers* 2022 14, 2287. <https://doi.org/10.3390/POLYM14112287>.
- Wang, Z., Shen, D., Wu, C., Gu, S., 2018. State-of-the-art on the production and application of carbon nanomaterials from biomass. *Green. Chem.* 20, 5031–5057. <https://doi.org/10.1039/C8GC01748D>.
- Waseem, W., Noor, R.S., Umair, M., 2024. The anaerobic transformation of agricultural waste for bioethanol production. *Biomass—Convers. Biorefin.* 14, 14163–14174. <https://doi.org/10.1007/S13399-023-04143-7/METRICS>.
- Wijitkosum, S., Jiwnok, P., 2019. Elemental composition of biochar obtained from agricultural waste for soil amendment and carbon sequestration, 3980 9 *Appl. Sci.* 2019 9, 3980. <https://doi.org/10.3390/APP9193980>.
- Wu, X., Nawaz, S., Li, Y., Zhang, H., 2024. Environmental health hazards of untreated livestock wastewater: potential risks and future perspectives, 2024 31:17 31 *Environ. Sci. Pollut. Res.* 24745–24767. <https://doi.org/10.1007/S11356-024-32853-6>.
- Yahya, E.B., Abdul Khalil, H.P.S., Ahmad, M.I., Rizal, S., Muhammad, S., 2023a. Cleaner approach of preparing antibacterial bioaerogel scaffolds using oil palm waste nanocellulose. *Ind. Crops Prod.* 191, 115897. <https://doi.org/10.1016/J.INDCROP.2022.115897>.
- Yahya, E.B., Abdul Khalil, H.P.S., Ahmad, M.I., Rizal, S., Muhammad, S., 2023b. Cleaner approach of preparing antibacterial bioaerogel scaffolds using oil palm waste nanocellulose. *Ind. Crops Prod.* 191, 115897. <https://doi.org/10.1016/J.INDCROP.2022.115897>.
- Yallappa, S., Deepthi, D.R., Yashaswini, S., Hamsanandini, R., Chandrasasad, M., Ashok Kumar, S., Hegde, G., 2017. Natural biowaste of Groundnut shell derived nano carbons: Synthesis, characterization and its in vitro antibacterial activity. *Nano-Struct. Nano-Objects* 12, 84–90. <https://doi.org/10.1016/J.NANOSO.2017.09.009>.
- Yan, N., Cao, J., Wang, J., Zou, X., Yu, X., Zhang, X., Si, T., 2024. Seed priming with graphene oxide improves salinity tolerance and increases productivity of peanut through modulating multiple physiological processes. *J. Nanobiotechnol.* 22, 1–18. <https://doi.org/10.1186/S12951-024-02832-7/FIGURES/7>.
- Yu, H., Wang, M., Cao, J., She, Y., Zhu, Y., Ye, J., Abd El-Aty, A.M., Hacimüftüoğlu, A., Wang, J., Lao, S., 2021. Dual-mode detection of organophosphate pesticides in pear and Chinese cabbage based on fluorescence and AuNPs colorimetric assays. *Food Chem.* 364, 130326. <https://doi.org/10.1016/J.FOODCHEM.2021.130326>.
- Yuan, S., Hou, Y., Liu, S., Ma, Y., 2024. A comparative study on rice husk, as agricultural waste, in the production of silica nanoparticles via different methods, 1271 17 *Materials* 2024 17, 1271. <https://doi.org/10.3390/MA17061271>.
- Yuan, W., Gong, Z., Wang, G., Zhou, W., Liu, Y., Wang, X., Zhao, M., 2018. Alkaline organosolv pretreatment of corn stover for enhancing the enzymatic digestibility. *Bioresour. Technol.* 265, 464–470. <https://doi.org/10.1016/J.BIORTECH.2018.06.038>.
- Zabidi, N.A., M.S.A. Fuad, I.S.M.A. Tawakkal, M.S.M. Basri, S.H. Othman, 2023. Mechanical, thermal and antimicrobial properties of PLA/Jackfruit skin composites containing thymol and nanocellulose. *Mater. Today Proc.* <https://doi.org/10.1016/J.MATPR.2023.01.397>.
- Zainab, R., Hasnain, M., Ali, F., Abideen, Z., Siddiqui, Z.S., Jamil, F., Hussain, M., Park, Y.K., 2024. Prospects and challenges of nanopesticides in advancing pest management for sustainable agricultural and environmental service. *Environ. Res.* 261, 119722. <https://doi.org/10.1016/J.ENVRES.2024.119722>.

- Zaki, M., Atiqah, M.S.N., Khalil, H.P.S.A., Ikram, H., Alfatah, T., Mistar, E.M., Adisalamun, A., Yahya, E.B., 2022. Microbial enhancement of nanocellulose isolation from sawn timber industrial wastes and fabrication of biocomposite membranes. *Bioresour. Technol. Rep.* 20, 101242. <https://doi.org/10.1016/J.BITEB.2022.101242>.
- Zhong, X., Su, G., Hao, L., Chen, H., Li, C., Xu, H., Zhou, H., Zhou, X., 2024. Foliar application of glycine-functionalized nanopesticides for effective prevention and control of root-knot nematodes via a targeted delivery strategy. *Pest Manag Sci.* 80, 2120–2130. <https://doi.org/10.1002/PS.7948>.
- Zhou, Y., He, J., Chen, R., Li, X., 2022. Recent advances in biomass-derived graphene and carbon nanotubes. *Mater. Today Sustain.* 18, 100138. <https://doi.org/10.1016/J.MTSUST.2022.100138>.