Agricultural Wastes-Derived Nanoparticles for Composites Materials Production: A Review on Synthesis, Properties and Applications

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ABSTRACT

The increasing global agricultural waste burden poses environmental and health challenges while offering a resource for sustainable materials. In Africa alone, millions of tonnes of agricultural wastes such as rice husks, sugarcane bagasse, and palm kernel shells are generated annually. This review examines nanoparticle synthesis from agricultural-based waste as potential reinforcing materials in addition to several other applications. Nanoparticles obtained from agro-based wastes were highlighted as potent materials for multiple applications including water purification, nano-fertilizers, drug delivery and composites. While synthesis protocol for nanoparticles is widely available from top-down to bottom-up approaches, challenges still remain on scalability due to variable waste composition, standardization of the protocols and nanoparticle toxicity. Thus, recommendations for future research, development of scalable synthesis methods, exploring new trend and novel applications are outlined.

Keywords: Sustainable materials, environmental pollution, synthesis, circular economy, remediation, agro-waste.

INTRODUCTION

Agricultural wastes are unused or residual materials generated from agricultural produce and agro-industrial by-products, such as crop residues, animal waste, and other associated waste streams. Agricultural wastes pose significant environmental and health risks but offers a resource opportunity for sustainable materials development [1]. Globally, approximately 1.3 billion tonnes of agricultural wastes are produced annually, driven by food loss and crop processing [2]. Nigeria alone produces about 30-40 million tonnes of agricultural wastes including rice husks, sugarcane bagasse, cassava peels, and palm kernel shells, contribute to environmental pollution due to inadequate treatment and disposal [3,4]. Rising population growth and expansion in agricultural and industrial activities exacerbate this issue, necessitating innovative waste management solutions.

Improper disposal methods, such as open burning and open field decomposition, release greenhouse gases (e.g., CH_4, NO_2, CO), contributing to global warming [5]. The World Health Organization (WHO) reports that air pollution, including those of agricultural waste combustion generates smog, which causes 7 million premature deaths annually, including 543,000 children [6,7]. Challenges such as poor public sensitization, insufficient technical expertise, limited recycling infrastructure and weak government policies hinder effective waste management [4]. Additionally, the transportation of raw agricultural produce to urban centers in developing countries, coupled with challenges in collection and processing, results in increased waste accumulation in markets, stores, residential areas, and dumping sites.

Nanoparticles (NPs) derived from agricultural wastes offer a promising avenue for valorization, leveraging their biocompatible, optical, and high-surface-area properties for applications in water purification, nano-fertilizers, drug delivery, and advanced polymer composites [8]. However, their safe application depends on understanding their toxicity, which varies with physicochemical properties, waste source, and synthesis method. For example, silica NPs from rice husk ash are often biocompatible, while silver NPs from corn stover may induce cytotoxicity at high concentrations due to reactive oxygen species generation [9].

This review synthesizes recent developments in the synthesis of NPs from agricultural wastes, focusing on waste sources, top-down and bottom-up synthesis approaches, properties, applications, and challenges such as scalability, standardization, and toxicity. By integrating specific insights from developing countries such as in Africa with global trends, it addresses a critical gap in the literature on sustainable nanotechnology and waste management, offering a roadmap for researchers and policymakers to harness agricultural wastes for environmental and economic benefits.

Agricultural Wastes: Types and Constituents

Agricultural wastes are categorized into plant-based (e.g., corn stalks, sugarcane bagasse, rice husk) and animal-based (e.g., chicken feathers, cow dung) [10,11,12]. They can further be classified into either field waste or process waste. Field wastes are residues that remain in the field after crop harvesting, comprising components such as leaves, stalks, seed pods, and stems. Processed wastes, such as husk, bagasse and molasses, are generated during the conversion of crops into valuable products [13,8]. Common agricultural wastes are shown in Plate 1

Plate 1: Agricultural wastes: (A) Palm kernel shell, (B) Rice husk (C) Sugarcane bagasse (D) Bamboo leaf (E) Groundnut shell (F) Maize cob

The nature and composition of agricultural wastes vary depending on the specific agricultural practices, crop or animal type, and production system. These wastes can be categorized by physical form into solid, liquid, and slurry types [14]. Solid Wastes are the post-harvest wastes or byproducts generated from agricultural activities such as crop residues (Stalks, stems, leaves, husks, fruit, vegetable peels, and bagasse), animal manure and bedding (excreta from livestock, along with materials used for animal bedding, particularly, straw and sawdust [14,15]. Liquid Wastes comprise liquid byproducts from agricultural activities including animal urine and liquid excreta from livestock and wastewater from cleaning animal housing or processing facilities. Slurry Wastes consist of a mixture of solid and liquid components such as combined manure and wastewater from livestock operations. These waste types offer an eco-friendly alternative to synthetic chemical reinforcements for NP production, reducing reliance on energy-intensive and environmentally harmful conventional methods [16]. For example, solid wastes like rice husks have been used to synthesize biocompatible silica NPs, while liquid wastes can serve as reaction media for NP synthesis [14].

Consequently, the waste types offer a renewable alternative to synthetic chemical reinforcements for synthesizing nanoparticles, reducing reliance on energy intensive and environmental harmful conventional methods [16]. The production process leverages on existing agricultural outputs, minimizing resources and energy demands offering potential cost reductions in materials procurement and waste management though safety risks associated with the materials need evaluation [14].

The percentage composition of agricultural waste varies significantly based on factors such as the specific agricultural activity, geographical location, and the types of crops or livestock [17,18], Agricultural plant-based waste primarily comprises a wide range of cellulose (21 to 45%), hemicellulose (15 to 33%), and lignin (5 to 24%) [19]. Due to its complex structure, lignocellulose is difficult to break down, thereby posing significant challenges for efficient utilization of agricultural waste. Their lower density compared to other inorganic fibers however makes them favorable for reinforcement. Nonetheless, their strong affinity for water, due to hydroxyl groups, limits their applicability in moisture-sensitive applications [20]. Lignocellulose biomass ashes are composed of macroelements including calcium, potassium, phosphorus, and sulfur, with low levels of toxic elements such as arsenic and lead [21]. Agricultural waste is also an abundant source of valuable compounds, including proteins, fatty acids, and bioactive compounds [22]. These properties make them ideal for sustainable reinforcements, despite processing challenges [23].

Environmental Impact of Agricultural Wastes

Common waste disposal methods used by most farmers in developing countries include open-field disposal, landfilling, burning, and dumping residue into rivers. While these methods are cost-effective, they often lead to ecological degradation and ecotoxicological risks. Landfilling is the most common disposal methods. Unfortunately, many developing countries operate open dump sites rather than controlled landfills, resulting in air, water, and soil pollution through chemical transportation. Open-field disposal is widely practiced, with studies showing 45% of livestock farmers in Nigeria dispose their waste on open lands [24]. Burning remains another prevalent method, with 10% of farmers employing sun-dried and burned waste disposal [24]. River contamination occurs through direct waste discharge into water bodies. This facilitates the leaching of organic matter, nutrients, and pathogens, leading to widespread contamination. Furthermore, the leaching of contaminants from decomposing waste can pollute underground water and subsequently impact the ecosystem health [25]. These crude disposal techniques create environmental pollution havoc, degrading both abiotic and biotic components of ecological systems while threatening human health, plants, and animals. The effect and environmental impacts of agricultural wastes are summarised in Table 1

Table 1: Summary of the resulting pollutants and the effects of crude agricultural waste disposal

Pollutants	Health effects	Environmental effects	References
Carbon Monoxide	Respiratory issues, neurological damage	Air quality degradation	[26]
Nitrous Oxide	Respiratory problems; possible skin cancer arising from ozone layer depletion	Climate change and ozone layer depletion	[27]
Nitrogen dioxide	Respiratory problems, lung damage	Acid rain, water pollution, formation of haze and smog	[27]
Particulate Matter (PM)	Respiratory problems, lung cancer	Air quality degradation and visibility reduction	[28,29]
Sulfur Dioxide	Respiratory problems, lung damage	Acid rain and air quality degradation	[30]
|Ammonia	Respiratory issues, eye irritation	Ecosystem disruption and eutrophication	[30]
Polycyclic Aromatic	Cancer, reproductive issues	Ecosystem disruption and ecotoxicity	[31]

Hydrocarbons (PAHs)			
Volatile Organic Compounds (VOCs)	Cancer, neurological damage	Ecosystem disruption and ecotoxicity	[32]

Agricultural Waste Ash

Ashes are produced through controlled combustion of agricultural wastes. The most commonly available agricultural-waste ashes are from rice husk, palm leaf, sugarcane bagasse, coconut, bamboo leaf, neem husk, corn cob and wood waste [11,12]. These ashes are sustainable sources for nanoparticle synthesis, replacing synthetic chemicals that require energy-intensive processes and emit CO_2 [33]. Agricultural-waste ash has varying chemical compositions, depending on the type of waste (crop residue, nut shells, fruit waste, and animal waste) and combustion temperature (200-1200 °C). The principal constituents of agricultural wastes ash typically include: Silica (SiO_2), (40-80%), Alumina (Al_2O_3) (5-20%), Iron oxide (2-10%), Calcium oxide (5-30%), Magnesium oxide 2-10%), Carbon (5-20%), Potassium oxide (2-5%), Sodium oxide (1-3%), and Phosphorus pentoxide (1-5%) [34, 35]. These wastes, rich in oxides like silicon and magnesium, have demonstrated potential to enhance mechanical, physical, and thermal properties making them a viable reinforcement in metal matrix composites and polymer composites thereby reducing pollution from disposal [36]. Various researchers have explored using agricultural waste as reinforcement in composites, reporting improvements in physical, mechanical, and wear properties [37]. Some common examples of agricultural-waste used as reinforcement include bean pod ash, maize pod ash, rice husk ash, palm kernel ash and bamboo leaf ash [38,39].

Bhaskar et al. [40] investigated the effects of agricultural-waste ash reinforcement on aluminum-based metal matrix composites. They observed improvements in specific strength, yield strength, ultimate tensile strength, hardness, and corrosion resistance. Osunmakinde et al. [41] analyzed aluminum composites reinforced with selected agricultural residues and observed enhanced mechanical properties (hardness, yield, and tensile strengths). Yadav et al. [42] reviewed the use of eggshell and rice-husk ash as reinforcement in composites, noting increased tensile strength and hardness. The high silica content in many agricultural-waste ashes contributes to these enhanced physical and mechanical properties [43,44].

Agriculture-Based Nanoparticles

The morphology and crystalline structure of nanoparticles are evaluated by atomic force microscopy (AFM), scanning electron microscopy, X-ray diffraction and transmission electron microscopy (TEM). The synthesis of nanoparticles from agricultural waste has garnered significant popularity in advanced engineering materials research, due to their advantages over conventional micro-scale ash which include: larger surface area to volume, quantum-level effects, biocompatibility, uniform dispersion, and improved absorption. Other benefits of agriculture-based nanoparticles include high heterogeneity. This diversity offers possibility of combination with various compounds to obtain a wide range of nanoparticles of cellulose, pectin, metallic and metallic oxide (titanium oxide, silver, zinc oxide), or silica [45,46]. Various studies have demonstrated the potential of agricultural waste-derived nanoparticles in sectors ranging from renewable energy to waste water treatment. For example, researchers have successfully converted cassava periderm and maize stalk into high-purity silicon nanoparticles using a modified sol-gel method, demonstrating the practical applications of these materials in photovoltaic cells [3].

Current applications of NP widely include wastewater treatment, nano-fertilizers, and polymer composites, though scalability, and standardization are often required [47]. Applications of nanoparticles derived from agricultural wastes encompass biomedical, agricultural, energy, and environmental remediation systems [48]. The environmental benefits of this synthesis approach generally align with global sustainability goals.

Physicochemical Properties of Agricultural-Based Nanoparticles

The physicochemical properties of NP are mainly governed by their size and shape, as well as their interfacial characteristics. A key feature of NP is the significant alteration of their physical, thermal, chemical, and other properties as their size reduces. This size reduction can lead to the formation of particles with properties markedly different from their larger-scale counterparts [49]. The large surface area influenced chemical reactivity and can significantly affect their mechanical and electrical characteristics. The physical properties of a nanoparticles include the optical, electric and magnetic properties [50]. The surface layer of a nanoparticles consists of ions, surfactant and molecules which also define the behavior of the materials as much as the core. Agricultural nanoparticles are easily synthesized and can be designed and modified in a variety of ways, such as by varying their cores and surface layers to create materials with unique properties and functions. For example, Silver at microscale exhibits a characteristic silvery-white color while silver nanoparticles often appear yellow (orange, or even red, depending on their size and shape). This phenomenon results from shape-dependent electron interactions within the nanoparticles, leading to distinct light-matter interactions compared to larger silver particles in the observation of vibrant colors [51].

Synthesis of Nanoparticles from Agricultural Wastes

There are two major approaches for synthesizing nanoparticles; top-down and bottom-up approaches. These approaches are further sub-categorized into: physical, chemical, and biological processes based on the methods adopted as illustrated in Table 2 and Figure 1.

Table 2: Summary of the methods involved in the synthesis of agricultural wastes-based nanoparticles

Method	Principle	Example	Advantages	Disadvantages	References
Physical	Reduce the size of bulk materials through mechanical or energetic processes.	Ball milling, laser ablation, sputtering	Simple, scalable, good control over particle size and shape.	Can generate impurities, high energy consumption, and potential for particle agglomeration.	[52]
Chemical	Building nanoparticles from atoms or molecules through	Sol-gel method, chemical vapor deposition,	Precise control over composition and structure, high purity, versatile for various materials.	Complex procedures, potential for toxic byproducts, limited scalability.	[53]

	chemical reactions.	hydrothermal synthesis			
Biological	Utilizing biological systems (e.g., plants, bacteria) to synthesize nanoparticles.	Synthesis of silver nanoparticles using plant extracts, bacterial synthesis of metallic nanoparticles	Environmentally friendly, biocompatible, cost-effective.	Slow process, lower yield compared to chemical methods, potential for contamination.	[54]

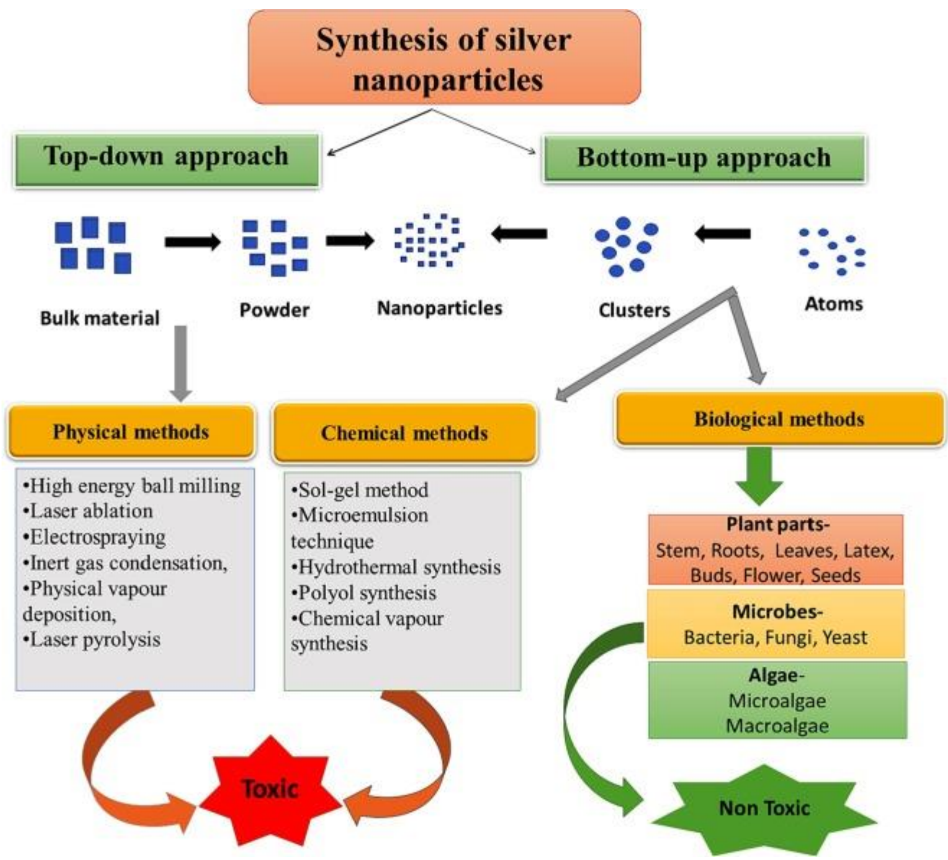

Figure 1: Methods involved in the synthesis of nanoparticles

The choice of synthesis method depends on the morphology of material, textural properties (pore size, particle size, and surface area), chemical and thermal stability. These methods allow the conversion of agricultural wastes into simpler structures by inducing changes in the physical/chemical properties of the raw material.

Top-down Approach

A top - down approach relies on macro structures being physically, mechanically or chemically reduced through a series of operations to reduce them into finer molecules. It is known as a destructive method and usually involve physical method, however, the change in particle size is caused by chemical and mechanical energy forces [55]. This method involves the usage of mechanical ball milling, arc discharge, wire explosion or chemical. [11].

a. Mechanical Ball Milling

Milling is a high-energy grinding process involving chipping and reducing a particle size, hence creating nanocrystalline powders by using balls media. It employs kinetic energy to degrade the material at nano scale. The size and characteristics of the nanoparticles produced is affected by initial particle size and nature and ball mill specification, rotation speed and the milling time [56]. The need for solvents is eliminated which reduces the energy consumption compared to traditional methods, thus, making it a popular technique in green chemistry. Milling Balls can be made of steel, rubber, alumina, ceramic, or alloys, or stainless steel. Milling outcomes are significantly influenced by the type of material used for the milling balls. Steel balls are effective for short-term size reduction, while alumina balls enhance surface area over longer periods of time, however, steatite-ceramic balls show superior durability and wear resistance compared to steel balls in NiTi powder production. This leads to a longer operational life for the ceramic balls, reducing the need for frequent replacements. Lower wear rate of ceramic balls, minimizes contamination, resulting in a purer NiTi powder product. The size of nanoparticles decreases with increase in milling time with larger balls leading to finer grains. They also introduce defects to the particles due to high impact energy; contamination from milling media can affect the properties of the nanoparticles. [57].

b. Chemical Etching

Chemical etching is a method of synthesis in which the surface of the material is modified through chemical reaction (e.g. Acids) and It involves the removal of materials by a chemical etchant resulting in the desired structure [49]. Chemical etching utilizing chemical reaction typically involves corrosive chemical (etchant), normally an acid, which dissolves unwanted material to produce the final design. The etchant's concentration must be carefully controlled to ensure it is sufficiently corrosive to remove unwanted material without compromising the bulk material's chemical composition or structural integrity [58]. Chemical etching offers the advantage of being stress-free, with no rough edges, and preserving material properties. This method is versatile, applicable to various wastes, but requires careful handling of corrosive chemicals to minimize environmental impact.

Bottom–up Approach

Bottom-up strategy is a technique where smaller components are used to make larger NPs which usually results in novel or enhanced functionalities. It works by the principle of molecular self-assembly. This involves the creation of nanoparticles through chemical reactions between atoms, ions, and molecules to form larger and more organized systems [59]. Stable structures are formed when molecules spontaneously organize while maintaining thermodynamic equilibrium via weak non-covalent bonds like hydrogen bonds, ionic bonds, and van der Waals bonds [60]. Bottom-up methods occur at gas-phase synthesis and liquid-phase formation, using technique such as plasma arcing, chemical vapor deposition process, metal organic decomposition, laser pyrolysis, molecular beam epitaxy, solgel method, hydrothermal, wet synthesis, and self-assembly processes [61] This approach promises better opportunities to obtain nanostructures with fewer defects, more homogeneous chemical composition, and excellent control of composition, size and shape. It is limited by the complex chemistry involved and the difficulties in scaling up the synthesis process. While some of these approaches are still in the early-stage development, others have only recently transitioned from research to commercial application in the field of nanopowder manufacturing. Further refinement is required to enhance their practical application and to align them with industrial scalability.

a. Sol-gel Method

The sol-gel method is a method primarily used for the synthesis of metal oxides and metal silicates. It is widely employed due to its simple procedures, particularly low processing temperature and mild chemical reactions. It offers advantage of producing high purity homogenous nanoparticles Adebisi et al. [3] synthesis silicon nanoparticles from cassava periderm, maize stalk and cob using sol–gel method. The products were confirmed with the aid of XRD, EDS and TEM within particle sizes less than 33 nm. Goswami and Mathur [62] also shows that silica nanoparticles can be produced from the ash of sugarcane bagasse by treating the ash with an alkaline solution to extract the silica before synthesizing the nanoparticles using sol-gel process. The procedure for obtaining silica gel from agricultural wastes are outlined in Figure 2.

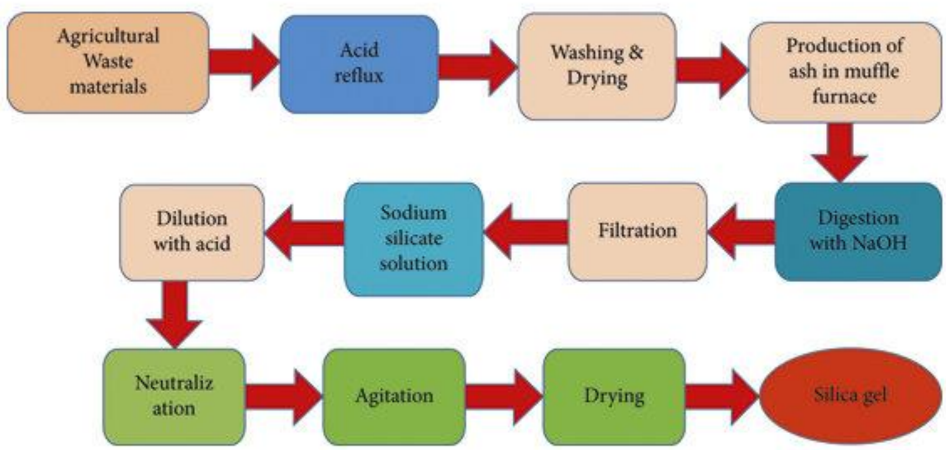

Figure 2: The process flow diagram for making silica gel from agricultural waste

B. Hydrothermal Method

In hydrothermal method, nanoparticles are synthesized from agricultural-wastes at high temperature (80 – 400 °C) and high vapor pressures (100kpa) with the aid water or polar inorganic solvents over a prolonged period of times [63]. The reactions take place in sealed autoclave kept above the boiling point of the solvent. These conditions facilitate the nucleation and growth of nanoparticles, often resulting in precise control over particle size, morphology, and surface [64]. This method relies on the solubility of minerals in hot water or polar inorganic solvent under high pressure autoclave and they are commonly used for the fabrication materials such as metal oxides and sulphates**.** Lower temperature (below 100 ^{o}C) is adopted for the synthesis of nanoparticles of agro-wastes derived from medicinal plants to preserve the integrity of the active components [65], though this possesses advantage of longer reaction time. Additionally, maintaining an alkaline pH (>8) is crucial for the process. This method widely benefits from energy reduction and low-chemical usage and has been particularly useful for controlling the size and purity of the nanoparticles, thus enhancing their suitability for various applications, from catalysis to environmental remediation [8].

Hybrid Approach: An Advanced Synthesis Method of Nanoparticle Processing

Hybrid approaches combine the elements of top-down and bottom-up approaches to achieve greater control over nanoparticle properties. This method leverages the advantages of multiple synthesis methods to achieve desired characteristics in the final nanoparticle. They offer a powerful toolkit for the synthesis of complex and sophisticated nanoparticles with tailored properties and functionalities. Yang et al. [66] explored a novel hybrid approach of combining several synthesis techniques allowing for the creation of complex multicomponent metal nanoparticles with up to four different metals. By combining the precision of bottom-up methods with the ability to shape and manipulate materials on a larger scale (top-down), researchers can gain greater control over the final nanostructure with unique properties and functionalities that are not achievable with either approach alone [67]. Integrating top-down and bottom-up techniques also allows for greater control over nanoparticle positioning and device assembly. An example of hybrid approaches includes sol-gel and chemical reduction, where metal oxide core is created using the sol-gel method and later reducing metal ions onto the surface to form a metallic shell.

One prevalent hybrid approach involves the use of both biological extracts and thermochemical reactions to produce silica nanoparticles from agricultural-wastes like rice husks and sugarcane bagasse. For instance, the acid leaching method combined with controlled calcination allows for the effective extraction of silica, which can then be converted into silicon nanoparticles [62]. This method is particularly valued for its ability to manipulate the size and purity of the nanoparticles, which are crucial for applications in industries such as electronics and pharmaceuticals. Hybrid semiconductor-metal nanoparticles exemplify this synergistic approach, integrating multiple functionalities from distinct materials. Through Advanced synthesis techniques, researchers can precisely control the component number, composition, shape, and interfacial characteristics, resulting in unique optical, electronic, and charge separation properties with potential applications in photo catalysis [68,65].

Table 3: Examples of nanoparticles synthesized from agricultural-wastes, the methods utilized and their applications

Agricultural-waste	Synthesized Nanoparticles	Synthesis Method	Morphology	Application	Size (nm)	References
Rice Husk	Silica Nanoparticles (SiO_2)	Sol-gel, Hydrothermal	Spherical, irregular	Water treatment, drug delivery	10-100	[69]
Wheat Straw	Cellulose Nanofibrils (CNFs)	Acid hydrolysis, Enzymatic hydrolysis	Fibrous	Composites, biomedicine	5-20	[70]
Wheat Straw	Lignin Nanoparticles	Solvent extraction, Enzymatic hydrolysis	Spherical, irregular	Adhesives, coatings	50-200	[71]
Banana Peels	Silver Nanoparticles (AgNPs)	Green synthesis (using plant extract)	Spherical	Antibacterial, antimicrobial	10-50	[72]
Banana Peels	Zinc Oxide Nanoparticles (ZnO NPs)	Green synthesis (using plant extract)	Spherical, rod-like	Antibacterial, photo catalysis	20-100	[68]
Coffee Grounds	Carbon Nanoparticles	Carbonization, Activation	Spherical, irregular	Adsorption, catalysis	10-50	[73]
Tea Leaves	Iron Oxide Nanoparticles (Fe_3O_4 NPs)	Green synthesis (using plant extract)	Spherical	Magnetic separation, drug delivery	10-30	[74]

Bamboo Leaf	Silica Nanoparticles (SiO_2)	Sol-gel, Combustion	Spherical, irregular	Composites, drug delivery	10-50	[75]

Development of Silica and Silver Nanoparticles from Agricultural-Based Wastes

Conventional silica production methods often rely on toxic precursors like tetraethyl orthosilicate (TEOS) and sodium silicate, which pose health and environmental risks. In addition, they are costly and energy-intensive. Recent research has prioritized developing greener and more cost-effective methods. [76,14,77]. Nanosilica can be produced from agricultural waste by different methods including chemical treatment, thermal treatment, and microbial treatment. Recent studies have explored the production of silicon and silica nanoparticles from agricultural wastes using sol-gel [78], chemical reduction [3]. Synthesis methods. Rice husk, maize cob, and cassava periderm have been successfully utilized as precursors for nanoparticle synthesis [69]. The sol-gel method, often modified with ethylene glycol or combined with freeze-drying, has shown promising results in producing high-purity amorphous silica nanoparticles with sizes ranging from 5 to 50 nm [3,69]. Higher silica purity is achieved by removing metallic impurities and other soluble pollutants from agricultural waste ash by acid leaching. This procedure is followed by sintering, to reduce the total carbon contents of the samples, and combustion processes. Acid leaching often involve chemicals that pose risk to the environment.

Optimization of synthesis parameters, such as pH, alkali concentration, and reaction time, can significantly improve nanoparticle yield and quality. Characterization techniques like XRD, FTIR, and TEM have confirmed the amorphous nature and high purity of the synthesized nanoparticles [69]. This eco-friendly approach to nanoparticle synthesis offers an environmentally friendly and economically viable solution for agricultural waste management while producing valuable materials for various industrial applications including hydrogen generation, optoelectronic devices, biological markers and construction of photocells. Bulk silicon has a bandgap of 1.12 eV, as SiNP size decreases below 10 nm, the bandgap increases to 1.8 eV, enabling efficient absorption of higher energy wavelengths thereby minimizes energy loss as heat and improving the overall energy conversion efficiency.

The synthesis of inorganic nanoparticles, such as silica and silver NPs, from agricultural wastes offers sustainable alternatives to conventional methods, addressing environmental concerns from crude disposal practices like open dumping [77]. Different Metal Nanoparticles like gold, silver, copper and Zinc have been observed in agricultural wastes. However, the ease of extraction and percentage synthesis is making organic synthesis of nanoparticle a matter of great concern. Methods that have been successful applied for the green synthesis of AgNPs from agricultural-based waste include: Sol-gel method, hydrothermal method, microwave-assisted method and ultrasonic-assisted method. AgNPs have unique physicochemical properties thereby exhibit potent antimicrobial, antifungal, and catalytic activities. Physical methods for the synthesis of nanoparticle often involve evaporation-condensation technique, typically carried out in a tube furnace under atmospheric pressure. This setup enables the evaporation of metal atoms, which subsequently condense into nanoparticles. The method however suffers from low production output and high energy consumption, but benefit from no use of toxic chemicals [79].

The chemical methods are the most popular but with few benefits. It involves three active components: metal precursors, reducing agents, and stabilizing/capping agents. The biosynthesis of the AgNPs using agricultural-waste typically involves preparation of the agricultural-waste extract and reduction of silver ions which occurs in two stages: nucleation and growth. Plant based materials are rich in various biomolecules, including polysaccharides, proteins, enzymes, and phenolic compounds, which act as reducing and stabilizing agents in AgNP synthesis. The extract containing biomolecules, is mixed with a silver salt solution (e.g., silver nitrate). The biomolecules present in the extract reduce the silver ions (Ag^+) to silver atoms (Ag^0), which subsequently aggregate to form AgNPs. The exact mechanism of reduction and stabilization varies depending on the specific agricultural-waste material and the experimental conditions (e.g., pH, temperature, and reaction time). The process is often completed within hours at room temperature or slightly elevated temperatures. AgNPs have found applications in industrial, pharmacological, and medicinal fields, exhibiting antibacterial, antifungal, and anticancer properties [80].

Development of Organic Nanoparticles

Various biomass sources, including sago bark, oil palm leaves, corn straw and groundnut shells have been successfully converted into carbon nanoparticles using simple pyrolysis techniques [81,82,83]. These nanoparticles exhibit high carbon content, porous structures, and particle sizes ranging from 35-85 nm. The resulting materials demonstrate excellent electrochemical performance, with specific capacitances of up to 180 F/g for supercapacitor applications [84]. and capacities of 546 mAh/g for lithium-ion battery anodes [85]. Notably, these carbon nanomaterials show remarkable stability, retaining 93% capacitance after 10,000 cycles [84].

Chidambaram et al. [86] reported the effectiveness of groundnut shell-derived carbon nanosheets in wastewater treatment, reducing biochemical oxygen demand (BOD) and chemical oxygen demand (COD) by over 70%. The study highlighted the eco-friendly and cost-effective nature of this approach. Further reports by Akpeji et al. [87] on groundnut shell utilization indicated successful synthesis of zinc oxide nanoparticles, carbon dots, as well as their nanocomposites. Hegde et al. [81] and Nasir et al. [88] reviewed the production of carbon nanoparticles and other nanostructures from palm kernel shells using pyrolysis vapor deposition, hydrolysis, and chemical composition.

Development of Nanocellulose

Cellulose, the Earth's most abundant and environmentally sustainable polymer, serves as a foundational feedstock for nanocellulose production. Nanocellulose refers to cellulosic materials with at least one dimension below 100 nm [89]. Nanocellulose exists in various forms such as cellulose nanocrystals (CNCs), cellulose nanofibers (CNFs), and bacterial nanocellulose (BNC) [90]. Extraction methods include chemical, mechanical, and chemo-mechanical treatments, with acid hydrolysis being a widely employed technique [91]. Nanocellulose has successfully been synthesized from diverse biomass sources, including sugarcane bagasse [92], corncob residue [93], and lignocellulosic materials like ragi stalk, mango wood, and groundnut husk [94]. Nanocellulose exhibits some remarkable properties like biodegradability, renewability, low density, high strength, high stiffness and ability to modify its surface chemistry.

Nanocellulose is a versatile material and show suitability for diverse applications towards variety of applications such as heavy metals, pharmaceuticals, medicines, textiles, barrier and reinforcing polymers [95]. Its light molecular weight also allows for effective synthesis with other substances, enhancing its applicability. Surface functionalization of nanocellulose, often through the addition of charged groups, can increase interfibrillar repulsion and contributes to more energy-efficient processing [96]. The preparation of nanocellulose from lignocellulosic feedstocks typically involves two main stages: pretreatment and extraction. The pretreatment stage focuses on purifying cellulose from raw materials through processes like alkali treatment and bleaching, while the extraction stage transforms cellulose into nanocellulose using mechanical, chemical, or enzymatic methods [96].

Non-woody plants, with their porous structure and lower lignin content, are increasingly recognized as ideal sources for more efficient nanocellulose production [96]. Various factors influence the selection of pretreatment and extraction methods, including biomass type, desired nanocellulose properties, and production scale [97]. Nanocellulose exists in two primary forms: nanocrystalline cellulose (NCC) and nanofibrillated cellulose (NFC), both offering superior properties compared to original cellulosic fibers and conventional reinforcement materials like Kevlar or steel wires. Pure cellulose nanocrystals possess mechanical strength of 7000 MPa and Young's modulus of 100-140 GPa nanocellulose can achieve an elastic modulus of up to 220 GPa and tensile strength between 7.5–7.7 GPa [98,99].

Characterization of Nanoparticles

Characterization of agriculturally based nanoparticles is crucial for assessing their suitability for specific applications [100]. They are characterized with different techniques such as powder X-ray diffraction (XRD), Scanning Electron Microscopy (SEM), Energy Dispersive X-ray (EDX) spectrum, Transmission electron microscopy (TEM), and UV-Visible spectrum. The X-ray diffraction analysis is used to evaluate the structure and crystalline phases of the materials [101]. Scanning Electron Microscopy is used to study the morphology and the size of the nanoparticles while Transmission Electron Microscopy study the particle size of the material in nano-scale and the crystal structure [102,103]. The elemental composition of nanoparticles is analyzed by Energy Dispersive X-ray spectrum. The particle size of the nanoparticles and the optical properties are analyzed using the Dynamic Light Scattering (DLS) and UV-Visible spectroscopy, respectively [104]. These analyses mostly help in understanding the crystallinity, phase composition, and surface morphology, which are essential factors in applications like wastewater treatment and material science. Nanoparticles are beyond the resolution limit of optical microscopes. This is because their diameters are smaller than the wavelengths of visible light [105].

Applications of Nanoparticles Derived from Agricultural Wastes

Nanoparticles derived from agricultural wastes have various applications across different fields, including:

a) Agriculture

Agriculture-based nanoparticles can enhance crop productivity, minimize chemical usage, and improve soil health. They improve crop productivity by delivering nutrients and pesticides more efficiently to plants, minimizing environmental degradation through specific application, and improving plant resistance to pests, diseases and stress, often by acting as nanofertilizers, nanofungicides and nanopesticides with controlled release mechanisms. They can also be used in soil remediation and monitoring crop health through Nanosensors [62,48]

b) Water Treatment

Nanoparticles can be used for water treatment by removing pollutants such as heavy metals and microorganisms from water, making it safe for drinking and irrigation [8].. For example, titanium dioxide nanoparticles from agricultural waste have been proved to photo-catalytically destroy organic contaminants. Similar nanoparticles obtained from materials such as rice husks can effectively adsorb heavy metals from water [74]. Silver nanoparticles obtained from agricultural wastes can also sterilize water. Including these nanoparticle composites into filtering membranes can significantly improve water quality by removing water pollutants [74].

c) Military and Defense

Nanoparticles derived from agricultural wastes are increasingly being explored for military textile applications due to their economic viability and climate-friendly nature. They offer potential in various defense sectors, including chemical, biological, radiological, nuclear protection, and in developing advanced coatings, composites, and energetic materials [8,106]. Additionally, nanomaterials from agricultural sources are being investigated to replace chromate-based compounds, offering environmentally compliant corrosion protection, damage sensing, and self-healing mechanisms and "smart" sensing mechanism [107].

d) Medical and Biomedical

Nanoparticles derived from agricultural-wastes exhibit excellent biocompatibility, making them suitable for medical applications such as drug delivery, wound healing, tissue engineering and cancer photothermal therapy [108, 109]. They are utilized for theragnostic, combining diagnosis and treatment. Moreover, they can be used to create biosensor which detects chemical and biological agents.

e) Energy Storage

Nanoparticles improve the efficiency of solar cells, fuel cells, and batteries. In solar cells, nanostructured materials enhance light absorption and charge transport, leading to increased efficiency [110]. For fuel cells and batteries, nanoparticles can be used as electrode materials and electrocatalysts, improving power output and performance [111]. Nanostructured electrodes with high surface areas and engineered electrolytes boost energy and power densities in various battery types. In wind energy, lubricants containing nanoparticle reduce friction in turbines, while nanocoating provide de-icing and self-cleaning properties. Supercapacitors benefit from nanoparticle-based electrodes, exhibiting enhanced energy and power densities [97]. Nanocellulose and carbon-based nanomaterials derived from agricultural-waste are emerging as promising materials in electrochemical energy storage devices like batteries and supercapacitors due to their high surface area to volume ratio and mechanical strength [112] Cellulose-based nanomaterials have demonstrated potential in solar energy harvesting, energy storage systems, and mechanical energy harvesters with application in photovoltaic devices, lithium-ion batteries, supercapacitors, and triboelectric nanogenerators [112,97].

f) Catalysis

Nanoparticles can be used as catalysts for various chemical reactions, such as biodiesel production and pollution reduction. They have shown potential to improve reaction rates, reduce reaction temperatures, and increase yields [59]. Nanoparticles are used to catalyze reactions that help reduce pollutants in air and water. They are utilized in automotive exhaust systems to convert harmful emissions like carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOCs) into less toxic substances. They address challenges associated with traditional catalysts, such as waste formation and high costs Khaturia et al. [59] These nanocatalysts act as filters to remove harmful substances from air or water. Their small size facilitates molecular-level interaction with pollutants, accelerating reactions that neutralize or break down the contaminants, contributing to cleaner air, water, and soil. Magnetic nanocatalysts are particularly attractive due to the absence of mass transfer resistance, reduced deactivation, and high recovery rates during separation [57]

g) Food Packaging

Nanoparticles are increasingly being used to develop biodegradable and antimicrobial food packaging materials, addressing challenges in food preservation and environmental concerns. They present cost-effective and eco-friendly alternatives to traditional packaging materials [113]. The incorporation of nanoparticles improves mechanical and barrier properties of packaging materials, extending the shelf life of food products and enhances food safety. Large surface area and high aspect ratio of nanoparticles makes cellulose-based bio nanocomposites a promising biodegradable alternative to petroleum-based plastics. Nanoparticles, like silver or zinc oxide can provide antimicrobial properties, oxygen scavenging ability, and UV impermeability, thus inhibiting the growth of bacteria, fungi, and other microorganisms that are responsible for food spoilage [114].

Toxicity of Agricultural Waste-Derived Nanoparticles

Nanoparticles produced through chemical methods often face significant hurdles in clinical and agricultural applications due to concerns regarding their biocompatibility, inherent toxicity, and long-term stability. The residues of harsh chemicals can adhere to the nanoparticle surface, potentially causing adverse effects in biological systems. The National Institute of Environmental Health Sciences reports that materials developed down to the nano scale may be hazardous to the health of humans and animals as they are readily absorbed into the body via inhalation, ingestion, or skin absorption [115]. Their potential to interact with biological systems and the environment necessitates rigorous toxicological assessments. Importantly, not all NPs are inherently harmful; their toxicity depends on factors such as composition, size, shape, surface chemistry, and exposure pathways. While some agricultural waste-derived NPs, like cellulose, are generally regarded as safe (GRAS) by regulatory bodies like the U.S. Food and Drug Administration (FDA) for certain applications, others, such as silver NPs, require further scrutiny due to potential genotoxicity or environmental persistence [116].

Studies on silica nanoparticles from rice husk show low cytotoxicity in human cell lines at concentrations below 100 µg/mL, but long-term inhalation studies are needed to assess pulmonary effects [117]. The biodegradability and biocompatibility of cellulose nanoparticles derived from sugarcane makes them suitable for drug delivery applications. Their toxicity is affected by particle size and surface modification; for example, cationic cellulose NPs may disrupt cell membranes more than neutral ones [116]. Silver nanoparticles from corn stover exhibit strong antimicrobial properties but can induce oxidative stress in mammalian cells at high doses. Their environmental release, particularly in agricultural applications, requires monitoring to prevent soil microbial disruption [118]. Carbon nanoparticles from palm kernel shells may pose risks if released into aquatic systems, where they can bioaccumulate in organisms like fish, necessitating ecotoxicological assessment [119].

Key factors influencing toxicity on nanoparticle include:

1. **Composition**: Organic NPs like cellulose are generally biocompatible, whereas inorganic NPs like silver or titanium dioxide may release ions that disrupt cellular functions. For instance, silver NPs have shown antimicrobial benefits but can also induce toxicity in human cells at concentrations above 10 µg/mL [118].
2. **Size and Surface Area**: The size and surface area of nanoparticles (NPs) derived from agricultural wastes significantly influence their toxicity, affecting their reactivity, cellular uptake, and environmental interactions. Smaller NPs, typically 5–20 nm, exhibit higher surface-to-volume ratios, enhancing their chemical reactivity and ability to penetrate biological membranes compared to larger NPs (>100 nm). For example, cellulose NPs (<50 nm) from palm kernel shells can cross cell membranes, potentially inducing oxidative stress via reactive oxygen species (ROS) generation, while larger particles (>100 nm) are less likely to do so [19].
3. **Exposure Pathways**: Inhalation, ingestion, or dermal exposure affects toxicity outcomes. For example, airborne silica NPs from agricultural waste burning may pose respiratory

risks, while ingested cellulose NPs in nano-fertilizers are often excreted without significant harm [117,118].

4. **Concentration**; High concentrations can cause oxidative stress and damage to plant cells, resulting in reduced growth and lower crop yield, thereby impacting food safety and security. The incorporation of agricultural-based nanoparticles may exhibit beneficial effects at low dosages (≤5%), whereas higher concentrations may induce phytotoxic effects [47,120]. For example, while low concentrations of zinc oxide nanoparticles from banana peels can promote growth in chili plants at low concentrations (50 ppm), higher concentrations may induce phytotoxic effects, leading to reduced germination rates and overall plant health.

Regulatory Frameworks and Risk Assessment: Navigating the Policy Landscape

The rapid evolution of nanotechnology, particularly in the context of agricultural waste valorization, has outpaced the development of comprehensive regulatory frameworks. This creates significant challenges for commercialization and responsible deployment.

Inappropriate or insufficient regulatory framework for nanoparticles in agriculture create uncertainty for manufacturers, limiting market entry. For example, silver NPs from corn stover, used as antimicrobial agents, lack clear EPA guidelines on environmental release, unlike conventional agrochemicals [118,116]. Robust comparative assessment between nanoparticle-based formulations and conventional agrochemicals are needed to establish safety and efficacy standards, fostering public and regulatory acceptance [116]

Risk assessment criteria for nanoparticles, especially concerning their exposure to plants, soil, and soil microbiome components, are not yet fully established. This lack of a thorough understanding of potential risks hinders the development of appropriate safety protocols and public acceptance. The health effects and regulatory requirements for the application of nanomaterials are significant concerns that must be addressed. To navigate this policy landscape, future research needs to focus on providing sufficient data from field trials and pest-crop host systems to support the safety and efficacy claims of nanoparticle-based products. Collaborative efforts between researchers, industry, and regulatory bodies are essential to develop science-based regulatory guidelines that foster innovation while ensuring environmental and human safety. As global regulations tighten on emissions and hazardous waste, industries that proactively shift to green methods will benefit from both cost savings and regulatory compliance. By integrating comprehensive characterization, standardized testing, and regulatory oversight, the safe development of these NPs can be ensured, maximizing their benefits in sustainable applications while minimizing risks.

Emerging Trends and Novel Applications

The integration of nanomaterials with 3D printing technology has created versatile, multifunctional hybrid biomaterials for biomedical applications, particularly in tissue engineering and regenerative medicine [121]. This convergence transforms agricultural waste into functional nanostructures while advancing additive manufacturing capabilities for specialized applications in optics, tissue engineering, and custom manufacturing. Agricultural waste can be effectively transformed into materials suitable for 3D printing applications, offering eco-friendly alternatives to conventional manufacturing materials. Karsoun et al, [122] demonstrated that agricultural waste can be converted into paste form for liquid deposition 3D printing, with mechanical testing revealing strong and durable properties suitable for printing various products. Pemas et al. [123] specifically investigated tomato agricultural waste, developing polylactic acid (PLA) composite filaments with 5-10% tomato stem powder for fused filament fabrication, showing consistent tensile properties at 5% addition and notable antioxidant activity.

Rahman et al, [123] conducted a systematic review of 57 publications, confirming that agriculturally derived biowastes can be transformed into diverse materials including powders, fibers, and filaments for additive manufacturing, though optimization of mechanical properties remains necessary.

Challenges and Limitations

Challenges in developing effective nanocomposites include achieving uniform nanoparticle dispersion within the composite matrix, as the tendency for nanoparticles to agglomerate persists. Another challenge remains in achieving consistent quality and scalability of nanoparticle synthesis from agricultural-wastes due to the variability in the properties of agricultural wastes and the complex processing required [76]. There are significant knowledge gaps regarding the interactions of nanomaterials with plants and the environment, hindering their effective application in agriculture [125]. The variability in waste composition and the need for specific processing technologies to ensure consistent quality and properties of the nanoparticles are potential hurdles. For example, the ash content varies by an order of magnitude from woody (0.5%) to herbaceous materials (5%), while lignin content decreases from ~30% to 15%, directly affecting conversion efficiency and biofuel yields. This variability creates barriers to scale-up and commercialization of lignocellulosic biofuel technologies [126].

Although green synthesis methods are celebrated for their environmental benefits, they face limitations in terms of controlling the size, distribution, and morphology of the produced nanoparticles. Advances in top-down and bottom-up synthesis approaches show promise but require further refinement to enhance their practical application and to align them with industrial scalability. The initial investment in research, development and setting up production facilities can be significantly hindered by high initial costs and economic uncertainties [76].

Exposure to NPs has been linked to numerous adverse health effects, including neurological disorders like Alzheimer's and Parkinson's diseases. Respiratory issues, including asthma, lung cancer, and other lung-related conditions, are reported consequences of NP inhalation [126]. Studies have shown that fibrous carbon nanoparticles can induce lung edema, raising concerns similar to those associated with asbestos exposure. The risk of inadvertent human exposure to potentially harmful levels of these particles is a significant concern necessitating further research and robust safety measures [127]. A study utilizing the comet assay [128] demonstrated that nanoparticles can induce DNA damage in cells. Similarly, copper oxide nanoparticles have been shown to induce DNA damage in agricultural and grassland plants, leading to the accumulation of mutagenic DNA lesions and inhibit plant growth depending on concentration and exposure time. These genotoxic effects of NPs may pose a health risk when ingested leading to cancer. High concentrations can cause oxidative stress and damage to plant cells, resulting in reduced growth and lower crop yield, thereby impacting food safety and security [120]. The incorporation of agricultural-based nanoparticles exhibits beneficial effects at low dosages (≤5%), whereas higher concentrations prove disastrous [47]

Future Outlook

Integration with Advanced Technologies

The future of agricultural waste-derived nanoparticles will be profoundly shaped by their integration with advanced technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and precision agriculture systems. The IoT will facilitate real-time monitoring of environmental conditions, crop health, and soil parameters. When combined with nanoparticle applications, this allows for truly precise and responsive interventions. For example, autonomous sensors and GPS systems can efficiently monitor crop growth and soil conditions, enabling the precise application of nano-nutrients for optimal crop improvement. This synergy will lead to highly efficient resource utilization, minimizing waste and maximizing productivity in agricultural systems.

Precision agriculture, enhanced by these integrated technologies, will enable dynamic adjustment of nanoparticle delivery systems based on real-time data. This means fertilizers and pesticides can be applied exactly where and when needed, reducing overall chemical use and further mitigating environmental impact. Such integration will move the field towards truly intelligent and sustainable agricultural practices.

CONCLUSION

The valorization of agricultural wastes into nanoparticles, as outlined in this review, provides a transformative approach to addressing the global waste burden while promoting sustainable nanotechnology. By utilizing wastes such as rice husks, sugarcane bagasse, and palm kernel shells, researchers have synthesized NPs like silica, cellulose, and silver, with applications in water purification, agriculture, biomedical fields, and energy storage. Challenges such as inconsistent waste composition, scalability, and toxicity (e. g., silver NP genotoxicity at high doses) highlight the need for standardized protocols and thorough assessments. Studies are currently required on standardized methodologies to address waste variability. Incorporation of AI and IoT can significantly improve synthesis precision and monitor environmental impacts in real- time. The review pointed out the need for collaborative efforts across materials science, engineering, and environmental technology to develop safe and cost- effective NP composites, thus, promoting waste management in developing countries.

REFERENCES

[1] Koul, B., Yakoob, M. & Shah, M. P. (2022). Agricultural waste management strategies for environmental sustainability. *Environmental Research, 206, Article 112285*. https://doi.org/10.1016/j.envres.2021.112285

[2] Food and Agriculture Organization of the United Nations (FAO). (2019). The State of Food and Agriculture 2019: Moving forward on food loss and waste reduction. Rome: FAO. https://doi.org/10.4060/ca6030en

[3] Adebisi, J.A., Agunsoye, J.O., Ahmed, I.I., Bello, S.A., Haris, M., Ramakokovhu, M.M., & Hassan, S.B. (2020). Production of silicon nanoparticles from selected agricultural wastes. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2020.03.658

[4] Fapohunda, C., Kilani, A., Adigo, B., Ajayi, L., Famodimu, B., Oladipupo, O., & Jeje, A. (2021). A review of some agricultural wastes in Nigeria for sustainability in the production of structural materials. *Nigerian Journal of Technological Development*, 18(2), 120–128. https://www.ajol.info/index.php/njtd/article/view/212519

[5] Yingying, X., & Wang, X. (2024). Impact of agricultural activities on climate change: A review of greenhouse gas emission patterns in field crop systems. *Plants*, 13(16), Article 2285. https://doi.org/10.3390/plants13162285

[6] World Health Organization (WHO). (2018). Ambient air pollution: Health impacts. Geneva: WHO. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

[7] World Health Organization (WHO). (2021). Ambient air pollution: data portal WHO. https://www.who.int/data/gho/data/themes/air-pollution

[8] Nath, P. C., Ojha, A., Debnath, S., Sharma, M., Sridhar, K., Nayak, P. K., & Inbaraj, B. S. (2023). Biogeneration of valuable nanomaterials from agricultural-wastes: A comprehensive review. 13(2), Article 561. https://doi.org/10.3390/agriculturalnomy13020561

[9] Lew, T. T. S., Koman, V. B., Silmore, K. S., Seo, J. S., Gordiichuk, P., Park, J., ... & Strano, M. S. (2020). Carbon-based nanomaterials from agricultural waste: Environmental implications and applications. *Nano Today*, 34, Article 101008. https://doi.org/10.1016/j.nantod.2020.101008

[10] Oladele, I. O., Falana, S. O., Akinbamiyorin, M. I., Onuh, L. N., Taiwo, A. S., Adelani, S. O., & Olanrewaju, F. O. (2025a). Cyclic thermal treatment parameters of bagasse particle reinforced epoxy bio-composites for sustainable applications. *Discover Polymers*, 2(5), 1–22. https://doi.org/10.1007/s44324-024-00005-3

[11] Mohammad, I., AlBiajawi, R. E., & Khairunisa, M. (2022). An overview of the utilization and method for improving pozzolanic performance of agricultural and industrial wastes in concrete. Materials Today: Proceedings, 48(4), 778–783. https://doi.org/10.1016/j.matpr.2021.09.389

[12] Akeem, A., Raheem, B., & Ikotun, D. (2020). Incorporation of agricultural residues as partial substitution for cement in concrete and mortar – A review. *Journal of Building Engineering*, 31, Article 101328. https://doi.org/10.1016/j.jobe.2020.101328

[13] Bichang'a, D. O., Oladele, I. O., Alabi, O. O., Aramide, F. O., Oluseye, O., Borisade, S. G., Githinji, D. N., & Ojemaye, M. O. (2024). Comparative property investigation of raw and treated coconut shell biomass for potential polymer composite application. *Heliyon*, 10(1), Article e23549. https://doi.org/10.1016/j.heliyon.2023.e23549

[14] Jeevanandam, V., Osborne, W. J., & Samuel, J. (2023). Relationship between microbes and the environment for sustainable ecosystem services. In Relationship between microbes and the environment for sustainable ecosystem services (pp. 191–205). Elsevier. https://doi.org/10.1016/B978-0-323-89936-9.00010-2

[15] Oladele, I. O., Bichang'a, D. O., Borisade, S. G., Makinde-Isola, B. A., Akinbamiyorin, I., & Githinji, D. N. (2024). Recent advancements in the application of natural fiber/particulate based polymer composites in automotive industry: A review on sustainable development. *Matériaux & Techniques*, 112(4), Article 402. https://doi.org/10.1051/mattech/2024024

[16] Divyabharathi, R., Kalidasan, B., Sakthi Suriya Raj, J. S. & Chinnasamy, S. (2024). Recent advances in sustainable agricultural residue utilisation, barriers and remediation for environmental management: Present insights and future challenges. *Industrial Crops and Products*, 216, Article 118790. https://doi.org/10.1016/j.indcrop.2024.118790.

[17] Makinde-Isola, B. A., Taiwo, A. S., Oladele, I. O., Akinwekomi, A. D., Adelani, S. O., & Onuh, L. N. (2024a). Development of sustainable and biodegradable materials: A review on banana and sisal fibre based polymer composites. *Journal of Thermoplastic Composite Materials,* 37(4), 1519–1539. https://doi.org/10.1177/08927057231188588

[18] Ojo, A. O. (2023). An overview of lignocellulose and its biotechnological importance in high-value product production. *Fermentation,* 9(11), Article 990. https://doi.org/10.3390/fermentation9110990

[19] Riseh, R. S., Vazvani, M. G., Hassanisaadi, M., & Thakur, V. K. (2024). Agricultural wastes: A practical and potential source for the isolation and preparation of cellulose and application in agriculture and different industries. *Industrial Crops and Products*, 208, Article 117904. https://doi.org/10.1016/j.indcrop.2023.117904

[20] Makinde-Isola, B. A., Akinwekomi, A. D., Oladele, I. O., Adeyanju, B. B., Idowu, A. S., Adewumi, A. O., & Aladenika, A. K. (2024b). Plant fiber constituents and impact of environmental degradation on the physical, hardness and thermal properties of banana-sisal fibre hybrid reinforced epoxy composites. *Journal of Materials Science Research and Reviews,* 7(3), 480–492.

[21] Zając, G., Szyszlak-Bargłowicz, J., Gołębiowski, W., & Szczepanik, M. (2018). Chemical characteristics of biomass ashes. *Energies*, 11(11), Article 2885. https://doi.org/10.3390/en11112885

[22] Dwivedi, S., Tanveer, A., Yadav, S., Anand, G., & Yadav, D. (2022). Agricultural-wastes for cost-effective production of industrially important microbial enzymes: An overview. In P. Chow-Dhary, S. Mani, & P. Chaturvedi (Eds.), Microbial biotechnology: Role in ecological sustainability and research (pp. 435–460). Wiley

[23] Zhu, Z., Gavahian, M., Barba, F. J., Roselló-Soto, E., Kovačević, D. B., Putnik, P., & Denoya, G. I. (2020). Valorization of waste and by-products from food industries through the use of innovative technologies. In Agri-food industry strategies for healthy diets and sustainability (pp. 249–266). Academic Press. https://doi.org/10.1016/B978-0-12-817226-1.00011-4

[24] Olusoji, A.J. & Charles, O.S. 2016. Livestock waste management practices in Oyo state, Nigeria. *J. Environ. Waste Manage*., 3: 139-141

[25] Matemilola, S., & Elegbede, I. (2017). Food loss and waste in Nigeria: A review. *Annals of Agricultural Sciences*, 64(2), 190–197. https://doi.org/10.1016/j.aoas.2017.08.001

[26] Sai, D. P., Amit, U. R., Alqamah, S., Juan, L. G., Owen, T., Dawid, W., Katarzyna, S., & Pawan, G. (2024). Review of agricultural biomass burning and its impact on air quality in the continental United States of America. *Environmental Advances*, 17, Article 100546. https://doi.org/10.1016/j.envadv.2024.100546

[27] Chaitanya, P., Upadhyay, E., Singh, D. D., & Singh, V. (2022). Health risk assessment linked to critical air pollutants' exposure. *Annals of Medical and Health Sciences Research*, 12(8), 194–200.

[28] Capozzi, V., Raia, L., Cretella, V., De Vivo, C., & Cucciniello, R. (2022). The impact of meteorological conditions and agricultural waste burning on PM levels: A case study of Avellino (Southern Italy). *International Journal of Environmental Research and Public Health*, 19(19), Article 12246. https://doi.org/10.3390/ijerph191912246

[29] Kyung, S. Y., & Jeong, S. H. (2020). Particulate-matter related respiratory diseases. *Tuberculosis and Respiratory Diseases*, 83(2), 116–121. https://doi.org/10.4046/trd.2019.0025

[30] Khalaf, E., Mohammadi, M. J., Sulistiyani, S., Ramírez-Coronel, A. A., Kiani, F., Jalil, A. T., Almulla, A. F., Asban, P., & Farhadi, M. (2022). Effects of sulfur dioxide inhalation on human health: A review. *Reviews on Environmental Health*, 39(2), 331–337. https://doi.org/10.1515/reveh-2022-0237

[31] Fakinle, B. S., Odekanle, E. L., Ike-Ojukwu, C., Sonibare, O. O., Falowo, O. A., Olubiyo, F. W., Oke, D. O., & Aremu, C. O. (2022). Quantification and health impact assessment of polycyclic aromatic hydrocarbons (PAHs) emissions from crop residue combustion. *Heliyon*, 8(3), https://doi.org/10.1016/j.heliyon.2022.e09113

[32] Hussain, M. S., Gupta, G., Mishra, R., Patel, N., Gupta, S., Alzarea, S. I., Kazmi, I., Kumbhar, P., Disouza, J., Dureja, H., Kukreti, N., Singh, S. K., & Dua, K. (2024). Unlocking the secrets: Volatile organic compounds (VOCs) and their devastating effects on lung cancer. *Pathology - Research and Practice*, 255, Article 155157. https://doi.org/10.1016/j.prp.2024.155157

[33] Melchor-Martínez, E. M., González-González, R. B., & Iqbal, H. M. N. (2022). Biodegradation of polyethylene terephthalate (PET) microplastics by mealworms: A solution to plastic pollution? *Frontiers in Environmental Chemistry*, 3, Article 824111. https://doi.org/10.3389/fenvc.2022.824111

[34] Rolka, E., Wyszkowski, M., & Kawałko, D. (2024). Characterizations of ash derived from the crops' waste biomass for soil improvement and assisted phytoremediation. *Biocatalysis and Agricultural Biotechnology*, 62, Article 103444. https://doi.org/10.1016/j.bcab.2024.103444

[35] Abioye, A. M., Ani, F. N., & Muhammad, M. S. (2024). Critical review of the role of ash content and composition in biomass pyrolysis. *Frontiers in Fuels*, 2, Article 1378361. https://doi.org/10.3389/ffuel.2024.1378361

[36] Parveez, B., Maleque, M. A., & Jamal, N. A. (2021). Influence of agro-based reinforcements on the properties of aluminum matrix composites: a systematic review. *Journal of Materials Science*, *56*(29), 16195–16222. https://doi.org/10.1007/s10853-021-06305-2

[37] Oladele, I. O., Betiku, O. T., Ajileye, O. J., Adediran, A. A., Aladejebi, O. A., & Talabi, S. I. (2022). Development and characterization of CaCO3-calcinated cow bone-derived CaO/P2O5 particulate hybrid reinforced polypropylene composites. *Journal of Chemical Technology and Metallurgy*, 57(6), 1129–1141.

[38] Owoeye, S. S., Folorunso, D. O., Aramide, F. O., & Okotie, B. (2024). Microwave energy assisted fabrication and characterization of 45S5 bioglass-ceramics using bio-wastes as alternative resources for biomedical applications. *Ceramics International*, 50(8), 12746–12762. https://doi.org/10.1016/j.ceramint.2024.01.179

[39] Ben, F., & Olubambi, P. A. (2024). Synthesis and structural analysis of calcined poultry manure for hydroxyapatite development. *Materials Research Express*, 11(6), Article 062004. https://doi.org/10.1088/2053-1591/ad5642

[40] Bhaskar, K., Dhananjay, P., Rajesh, K. S., & Pradeep, K. S. (2021). A survey on effect of agro waste ash as reinforcement on aluminium base metal matrix composites. *Open Journal of Composite Materials*, 11(4), 118–133. https://doi.org/10.4236/ojcm.2021.114010

[41] Osunmakinde, L., Asafa, T. B., Agboola, P., Olanrewaju, O. F., & Aladejebi, O. A. (2023). Development of aluminum composite reinforced with selected agricultural residues. *Discover Materials*, 3(1), Article 33. https://doi.org/10.1007/s43939-023-00069-z

[42] Yadav, R., Dwivedi, V. K., & Dwivedi, S. P. (2021). Eggshell and rice husk ash utilization as reinforcement in development of composite material: A review. Materials Today: Proceedings, 43(Part 1), 426–433. https://doi.org/10.1016/j.matpr.2020.11.717

[43] Kulkarni, P., Siddeswarappa, B., & Kumar, K. (2019). A survey on effect of agricultural waste ash as reinforcement on aluminium base metal matrix composites. *Open Journal of Composite Materials*, 9(3), 312–326. https://doi.org/10.4236/ojcm.2019.93019

[44] Sharma, V., Meena, M. L., & Kumar, M. (2020). Effect of filler percentage on physical and mechanical characteristics of basalt fiber reinforced epoxy-based composites. *Materials Today: Proceedings*, 26(Part 2), 2506–2510. https://doi.org/10.1016/j.matpr.2020.02.533

[45] Elemike, E., Ekennia, A., Onwudiwe, D., & Ezeani, R. (2022). Agricultural-waste materials: Sustainable substrates in nanotechnology. In Agri-waste and microbes for production of sustainable nanomaterials (pp. 187–214). Elsevier. https://doi.org/10.1016/B978-0-12-823575-1.00022-6

[46] Abuzeid, H. M., Julien, C. M., Zhu, L., & Hashem, A. M. (2023). Green synthesis of nanoparticles and their energy storage, environmental, and biomedical applications. *Crystals*, 13(11), Article 1576. https://doi.org/10.3390/cryst13111576

[47] Feigl, G. (2023). The impact of copper oxide nanoparticles on plant growth: A comprehensive review. *Journal of Plant Interactions*, 18(1), Article 2243098. https://doi.org/10.1080/17429145.2023.2243098

[48] Osman, A. I., Zhang, Y., Farghali, M., Rashwan, A. K., El-Taher, A. M., El-Fatah Abou-Ziyan, A. M., ... & Yap, P.-S. (2024). Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review. *Environmental Chemistry Letters*, 22(2), 841–887. https://doi.org/10.1007/s10311-023-01682-3

[49] Bharat, B. (Ed.). (2017). Springer handbook of nanotechnology (4th ed.). Springer. https://doi.org/10.1007/978-3-662-54357-3

[50] Taylor-Smith, K. (2024). An introduction to the quantum mechanics of nanoparticles. AZoQuantum. Retrieved January 20, 2025, from https://www.azoquantum.com/Article.aspx?ArticleID=179

[51] Duman, H., Eker, F., Akdaşçi, E., Witkowska, A. M., Bechelany, M., & Karav, S. (2024). Silver Nanoparticles: A Comprehensive Review of Synthesis Methods and Chemical and Physical Properties. *Nanomaterials*, 14(18), 1527. https://doi.org/10.3390/nano14181527

[52] Al-Harbi, N., & Abd-Elrahman, N. K. (2025). Physical methods for preparation of nanomaterials, their characterization and applications: A review. *Journal of Umm Al-Qura University for Applied Sciences*, 11, 356–377. https://doi.org/10.1007/s43994-024-00165-7

[53] Yousefi, S., Makarem, M. A., & Rahimpour, M. R. (2023). Chemical vapor deposition by syngas on nanoparticles: Application to drug delivery. In Advances in synthesis gas: Methods, technologies and applications (Vol. 3, pp. 395–410). Elsevier. https://doi.org/10.1016/B978-0-323-91878-7.00015-0

[54] Garg, D., Sarkar, A., Chand, P., Bansal, P., Gola, D., Sharma, S., Khantwal, S., Surabhi, Mehrotra, R., Chauhan, N.M., & Bharti, R.K. (2020). Synthesis of silver nanoparticles utilizing various biological systems: mechanisms and applications—a review. *Progress in Biomaterials*, 1-15. https://doi.org/10.1007/s40204-020-00135-2

[55] González-González, R. B., Morales-Murillo, M. B., Martínez-Prado, M. A., Melchor-Martínez, E. M., Ahmed, I., Bilal, M., & Iqbal, H. M. N. (2022). Carbon dots-based nanomaterials for fluorescent sensing of toxic elements in environmental samples. *Chemosphere*, 300, Article 134515. https://doi.org/10.1016/j.chemosphere.2022.134515

[56] Pohshna, C., & Mailapalli, D. R. (2023). Modeling the particle size of nanomaterials synthesized in a planetary ball mill. *OpenNano*, 14, Article 100191. https://doi.org/10.1016/j.onano.2023.100191

[57] Ali Hosseini, S. (2022). Nanocatalysts for biodiesel production. *Arabian Journal of Chemistry*, 15(8), Article 104152. https://doi.org/10.1016/j.arabjc.2022.104152.

[58] Zulkepli, M. A., & Mohammad, N. (2020). Influence of HF etching time and concentration on Si wafer in the mixture solution of HF/HNO3/CH3COOH. *Journal of Sustainability Science and Management*, 15(2), 6–11. https://jssm.umt.edu.my/wp-content/uploads/2020/05/2.15.2pdf.pdf

[59] Khaturia, S., Chahar, M., Sachdeva, H., Sangeeta, & Maheshwari, C. B. (2020). A review: The uses of various nanoparticles in organic synthesis. *Journal of Nanomedicine and Nanotechnology*, 11(10), Article 543. https://doi.org/10.35248/2157-7439.19.10.543

[60] Senna, M. (2024). Chemical bonds in molecular aggregation – From drinking water to nanocomposites. *Citi Science,* 4(1), Article 2024.02. https://doi.org/10.60167/csj/v4i1.2024.02

[61] Sokolikova, M. S., & Mattevi, C. (2020). Direct synthesis of metastable phases of 2D transition metal dichalcogenides. *Chemical Society Reviews*, 49(12), 3952–3980. https://doi.org/10.1039/d0cs00143k

[62] Goswami, P., & Mathur, J. (2022). Application of agricultural-waste-mediated silica nanoparticles to sustainable agriculture. *Bioresources and Bioprocessing*, 9(1), Article 17. https://doi.org/10.1186/s40643-022-00496-5

[63] Akshaya, T., Aravind, M., Manoj Kumar, S., & Divya, B. (2022). Evaluation of in-vitro antibacterial activity against gram-negative bacteria using silver nanoparticles synthesized from Dypsis lutescens leaf extract. *Journal of the Chilean Chemical Society*, 67(2), 5477–5483. https://doi.org/10.4067/S0717-97072022000205477

[64] Lade, D. B., & Shanware, A. S. (2020). Phytonanofabrication: Methodology and factors affecting biosynthesis of nanoparticles. In Smart nanosystems for biomedicine, optoelectronics and catalysis (pp. 1–24). IntechOpen. https://doi.org/10.5772/intechopen.90918

[65] Elias, M. M., Said, M. M., Nassar, A. M. K., El-Naggar, M. E., & Abdel-Gawad, F. K. (2022). Biogenic synthesis of iron oxide nanoparticles using Bambusa arundinacea leaves for antibacterial and photocatalytic applications. *Applied Biochemistry and Biotechnology*, 194(12), 5953–5968. https://doi.org/10.1007/s12010-022-04083-2.

[66] Yang, H., Bradley, S. J., Wu, X., Chan, A., Waterhouse, G. I., Nann, T., Zhang, J., Kruger, P. E., Ma, S. & Telfer, S. G. (2018). General synthetic strategy for libraries of supported multicomponent metal nanoparticles. *ACS Nano*, 12(5), 4594–4604. https://doi.org/10.1021/acsnano.8b01022

[67] Singh, P., Singh, S., Boyina, B. M., Kandalam, S. K., Walski, T., & Bohara, R. (2024). Hybrid silver nanoparticles: Modes of synthesis and various biomedical applications. *Electron*, 2(2), Article e22. https://doi.org/10.1002/elt2.22

[68] Qahtan, T. F., Ibrahim, S. S., Al-Jumaili, M. H. A., & Alkubaisy, S. A. (2024). Green synthesis of ZnO nanoparticles using banana peel extract: Structural and optical properties. *Journal of Optics*, 53(2), 1030–1037. https://doi.org/10.1007/s12596-023-01349-5

[69] Yuan, S., Ma, Z., Hou, Y., Niu, S., Lekai, L., Liu, X., Wang, S., Xu, Z., & Ma, Y. (2024). Improving the grindability of rice husk-based green silica through pyrolysis process optimization employing the Taguchi method and response surface methodology. *CrystEngComm*, *26*(1), 128–142 . https://doi.org/10.1039/D3CE01016C

[70] Morcillo-Martín, R., Espinosa, E., Rabasco-Vílchez, L., Sanchez, L. M., de Haro, J., & Rodríguez, A. (2022). Cellulose nanofiber-based aerogels from wheat straw: Influence of surface load and lignin content on their properties and dye removal capacity. *Biomolecules*, 12(2), Article 232. https://doi.org/10.3390/biom12020232

[71] Kong, Z., Wang, Z., Chen, B., Li, Y., & Li, R. (2023). Effect of ball milling time on the microstructure and properties of high-silicon-aluminum composite. *Materials*, 16(17), Article 5763. https://doi.org/10.3390/ma16175763

[72] Gunjal, P. R., & Gaikwad, S. D. (2023). Green synthesis and characterization of silver nanoparticles using banana peel extract and their biological activity against representative microorganisms. *World Journal of Biology Pharmacy and Health Sciences*, 13(1), 425–439. https://doi.org/10.30574/wjbphs.2023.13.1.0048

[73] Nazar, M., Hasan, M., Wirjosentono, B., Gani, B. A., & Nada, C. E. (2024). Microwave synthesis of carbon quantum dots from Arabica coffee ground for fluorescence detection of Fe3+, Pb2+, and Cr3+. *ACS Omega*, 9(18), 20571–20581. https://doi.org/10.1021/acsomega.4c02254

[74] Rodríguez-Rasero, C., Alexandre-Franco, M. F., Fernández-González, C., Montes-Jiménez, V., & Cuerda-Correa, E. M. (2024). Valorizing tea waste: Green synthesis of iron nanoparticles for efficient dye removal from water. Antioxidants, 13(9), Article 1059. https://doi.org/10.3390/antiox13091059

[75] Neha, R., Saxena, A., & Mandal, A. (2022). Sustainable synthesis of silica nanoparticles from agricultural waste and their applications. *Materials Today: Proceedings,* 69(Part 2), 496–502. https://doi.org/10.1016/j.matpr.2022.08.042

[76] Flores-Contreras, E. A., González-González, R. B., Pizaña-Aranda, J. J. P., Parra-Arroyo, L., Rodríguez-Aguayo, A. A., Iñiguez-Moreno, M., ... & Melchor-Martínez, E. M. (2024). Agricultural waste as a sustainable source for nanoparticle synthesis and their antimicrobial properties for food preservation. *Frontiers in Nanotechnology*, 6, Article 1346069. https://doi.org/10.3389/fnano.2024.1346069

[77] Owoyemi, H. T., Oladele, I. O., & Adewuyi, B. O. (2020). Synthesis and characterization of silver nanoparticles from ecofriendly materials: A review. *International Journal of Engineering Research & Technology*, 9(9), 782–795.

[78] September, L. A., Kheswa, N., Seroka, N. S., & Khotseng, L. (2023). Green synthesis of silica and silicon from agricultural residue sugarcane bagasse ash - A mini review. *RSC Advances*, 13(2), 1370–1380. https://doi.org/10.1039/d2ra07490g

[79] Ramya, P., & Beena, M. (2021). Green synthesis of silver nanoparticles. International Journal of Pharmaceutical Sciences and Nanotechnology, 14(3), 5481–5488.

[80] Lee, S. H., & Jun, B.-H. (2019). Silver nanoparticles: Synthesis and application for nanomedicine. *International Journal of Molecular Sciences*, 20(4), Article 865. https://doi.org/10.3390/ijms20040865

[81] Hegde, S., Kumar, A. & Hegde, G. (2020). Synthesis of sustainable carbon nanospheres from natural bioresources and their diverse applications. In Sustainable nanotechnology: Strategies, products, and applications (pp. 293–310). American Chemical Society. https://doi.org/10.1021/bk-2020-1353.ch016.

[82] Zakaria, N. Z. J., Rozali, S., Mubarak, N. M., Zainal, Z., Yusof, N. A., & Alibe, I. M. (2024). A review of the recent trend in the synthesis of carbon nanomaterials derived from oil palm by-product materials. *Biomass Conversion and Biorefinery*, 14(1), 13–44. https://doi.org/10.1007/s13399-022-02430-3

[83] Mandala, R., Hegde, G., Kodali, D., & Kode, V. R. (2023). From waste to strength: Unveiling the mechanical properties of peanut-shell-based polymer composites. *Journal of Composites Science*, 7(8), Article 307. https://doi.org/10.3390/jcs7080307

[84] Bhat, V. S., Kanagavalli, P., Sriram, G., B, R. P., John, N. S., Veerapandian, M., Kurkuri, M. D., & Hegde, G. (2020). Low-cost, catalyst-free, high-performance supercapacitors based on porous nano carbon derived from agriculture waste. *Journal of Energy Storage*, 32, Article 101829. https://doi.org/10.1016/j.est.2020.101829

[85] Yu, K., Wang, J., Wang, X., Liang, J. & Liang, C. (2020). Sustainable application of biomass by-products: Corn straw-derived porous carbon nanospheres using as anode materials for lithium ion batteries. *Materials Chemistry and Physics*, 243, Article 122644. https://doi.org/10.1016/j.matchemphys.2020.122644

[86] Chidambaram, P. P., Ramalingam, K., Rakesh, S. S., Raja, K., Ramesh, P. T., Prabakaran, C., & Teja, M. (2024). Synthesis and characterization of groundnut shell carbon nanosheets for treating greywater: A step towards a circular economy. *Plant Science Today*, 11(sp4), 1–10. https://doi.org/10.14719/pst.5499

[87] Akpeji, B. H., Emegha, M. C., Onyenue, E. E., Meshack, O. Q., & Elemike, E. E. (2024). Synthesis and characterization of nanoparticles of ZnO, carbon dot and ZnO-carbon dot nanocomposite from groundnut shell wastes. *Journal of Applied Sciences and Environmental Management*, 28(6), 1771–1780. https://doi.org/10.4314/jasem.v28i6.16

[88] Nasir, S., Hussein, M. Z., Zainal, Z., Yusof, N. A., Zobir, S., & Alibe, I. M. (2019). Potential valorization of by-product materials from oil palm: A review of alternative and sustainable carbon sources for carbon-based nanomaterials synthesis. *BioResources*, 14(1), 2352–2388. https://doi.org/10.15376/biores.14.1.2352-2388

[89] Bačáková, L., Pajorová, J., Tomková, M. Z., Brož, A., & Bačák, P. (2019). Applications of nanocellulose and its derivatives in biomedicine and tissue engineering: An overview. *AIMS Bioengineering*, 6(4), 73–92. https://doi.org/10.3934/bioeng.2019.4.73

[90] Huang, J., Ma, X., Yang, G., & Alain, D. (2019). Introduction to nanocellulose. In Nanocellulose: From fundamentals to advanced applications (pp. 1–24). Wiley. https://doi.org/10.1002/9783527807437.ch1

[91] Kaur, G., Singh, H., & Singh, J. (2021a). UV-vis spectrophotometry for environmental and industrial analysis. In Green sustainable process for chemical and environmental engineering and science (pp. 49–68). Elsevier. https://doi.org/10.1016/B978-0-12-821883-9.00004-7

[92] Charoensopa, V., Poolsawat, O., & Sommano, S. R. (2024). Valorisation of lignocellulosic biomass: Chemical composition and functional properties of sugarcane bagasse for nanocellulose preparation. *Journal of Bioresources and Bioproducts*, 9(3), 533–548. https://doi.org/10.1016/j.jobab.2024.03.001

[93] Rajanna, M., Shivashankar, L. M., Honnebagi, O., Ramachandrappa, S. U., Betageri, V. S., Shivamallu, C., Shetty, R. H. L., Kumar, S., Amachawadi, R. G., & Kollur, S. P. (2022). A facile synthesis of cellulose nanofibers from corn cob and rice straw by acid hydrolysis method. *Polymers*, 14(20), Article 4383. https://doi.org/10.3390/polym14204383

[94] Prasannakumar, J., Prakash, G., Onkarappa, H., Suresh, B., & Basavarajappa, B. (2022). Synthesis and characterization of nanocellulose from lignocellulosic agricultural biomass by acid hydrolysis. *Asian Journal of Chemistry*, 34(10), 2639–2645. https://doi.org/10.14233/ajchem.2022.23900

[95] Abdullah, N. A., Rani, M. S. A., Mohammad, M., Sainorudin, M. H., Asim, N., Yaakob, Z., Razali, H. H., & Emdadi, Z. (2021). Nanocellulose from agricultural waste as an emerging material for nanotechnology applications – An overview. *Polimery*, 66(3), 157–168. https://doi.org/10.14314/polimery.2021.3.1

[96] Das, R., Lindström, T., Khan, M., Rezaei, M., & Hsiao, B. S. (2024). Nanocellulose preparation from diverse plant feedstocks, processes, and chemical treatments: A review. *BioResources*, 19(1), 1865–1924. https://doi.org/10.15376/biores.19.1.1865-1924

[97] Mahmoud, M. M., Chawraba, K., & El Mogy, S. A. (2024). Nanocellulose: A comprehensive review of structure, pretreatment, extraction, and chemical modification. *Polymer Reviews*, 64(3), 1–37. https://doi.org/10.1080/15583724.2024.2374929

[98] Ratry, L. A., & Siddique, M. B. M. (2024). The extraction process of nanocellulose from organic waste and incorporating it into biopolymers for mechanical property enhancement. *Future Sustainability*, 2(1), 14–24. https://doi.org/10.55670/fpll.fusus.2.1.2

[99] Khalid, M. Y., Al Rashid, A., Arif, Z. U., Ahmed, W., & Arshad, H. (2021). Recent advances in nanocellulose-based different biomaterials: types, properties, and emerging applications. *Journal of Materials Research and Technology*, 14, 2601-2623.

[100] Mitra, D., Adhikari, P., Djebaili, R., Thathola, P., Joshi, K., Pellegrini, M., Adeyemi, N. O., Khoshru, B., Kaur, K., Priyadarshini, A., Senapati, A., del Gallo, M., Das Mohapatra, P. K., Nayak, A. K., Shanmugam, V., & Panneerselvam, P. (2023). Biosynthesis and characterization of nanoparticles, its advantages, various aspects and risk assessment to maintain the sustainable agriculture: Emerging technology in modern era science. Plant Physiology and Biochemistry, 196, 103–120. https://doi.org/10.1016/j.plaphy.2023.01.017

[101] Khan, H. U., Yerramilli, A. S., D'Oliveira, A., Alford, T. L., Boffito, D. C., & Patience, G. S. (2020). Experimental methods in chemical engineering: X-ray diffraction spectroscopy—XRD. *The Canadian Journal of Chemical Engineering*, 98(11), 2255–2267. https://doi.org/10.1002/cjce.23747

[102] Eskandari, F., Gostariani, R., & Asadi Asadabad, M. (2020). Transmission electron microscopy of nanomaterials. In Electron crystallography (pp. 1–20). IntechOpen. https://doi.org/10.5772/intechopen.92212

[103] Aziz, A., Shaikh, H., Abbas, A., Zehra, K. E., & Javed, B. (2025). Microscopic techniques for nanomaterials characterization: A concise review. *Microscopy Research and Technique*, 88(2), 374–389. https://doi.org/10.1002/jemt.24799

[104] Ijaz, I., Gilani, E., Nazir, A., & Bukhari, A. (2020). Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles. *Green Chemistry Letters and Reviews*, 13(3), 223–245. https://doi.org/10.1080/17518253.2020.1802517

[105] Shi, X., Zhao, S., Wang, F., Jiang, Q., Zhan, C., Li, R., & Zhang, R. (2021). Optical visualization and imaging of nanomaterials. *Nanoscale Advances*, 3(4), 889–903. https://doi.org/10.1039/D0NA00945H

[106] Adeyanju, B. B., Adewuyi, B. O., Oladele, I. O., Daramola, O. O., Aramide, F. O., Adekunle, A. M., Talabi, H. K., Ademola, A., Adewumi, O. A., & Samson, I. A. (2024). Agricultural-based nanoparticles composite: A novel approach for enhanced ballistic applications. *Current Material Science: Research and Reviews,* 4(2), 1–10. https://doi.org/10.51594/cmsrj.v4i2.1627

[107] Sanyal, S., Park, S., Chelliah, R., Yeon, S.-J., Barathikannan, K., Vijayalakshmi, S., Jeong, Y.-J., Rubab, M., & Oh, D. H. (2024). Emerging trends in smart self-healing coatings: A focus on micro/nanocontainer technologies for enhanced corrosion protection. *Coatings*, *14*(3), 324. https://doi.org/10.3390/coatings14030324

[108] Zdraveva, E., Gaurina Srček, V., Kraljić, K., Škevin, D., Slivac, I., & Obranović, M. (2023). Agricultural-industrial plant proteins in electrospun materials for biomedical application. *Polymers,* 15(12), Article 2684. https://doi.org/10.3390/polym15122684

[109] Karnwal, A., Jassim, A. Y., Mohammed, A. A., Sharma, V., Al-Tawaha, A. R. M. S., & Sivanesan, I. (2024). Nanotechnology for healthcare: Plant-derived nanoparticles in disease treatment and regenerative medicine. *Pharmaceuticals*, 17(12), Article 1711. https://doi.org/10.3390/ph17121711

[110] Oladele, I. O., Adelani, S. O., Taiwo, A. S., Akinbamiyorin, I., Olanrewaju, O. F., & Orisawayi, A. O. (2025). Polymer-based nanocomposites for supercapacitor applications: A review on principles, production and products. *RSC Advances,* 15(11), 7509–7534. https://doi.org/10.1039/D4RA07329B

[111] Ghosh, S., & Subudhi, S. (2021). Developments in fuel cells and electrochemical batteries using nanoparticles and nanofluids. *Energy Storage*, 4(4), Article e288. https://doi.org/10.1002/est2.288

[112] Xiao, J., Li, H., Zhang, H., He, S., Zhang, Q., Liu, K., Jiang, S., Duan, G., & Zhang, K. (2022). Nanocellulose and its derived composite electrodes toward supercapacitors: Fabrication, properties, and challenges. *Journal of Bioresources and Bioproducts*, 7(4), 245–269. https://doi.org/10.1016/j.jobab.2022.05.003

[113] Baraketi, S., & Khwaldia, K. (2024). Nanoparticles from agri-food by-products: Green technology synthesis and application in food packaging. *Current Opinion in Green and Sustainable Chemistry*, 47, Article 100953. https://doi.org/10.1016/j.cogsc.2024.100953

[114] Ashfaq, A., Khursheed, N., Fatima, S. W., Anjum, Z., & Younis, K. (2022). Application of nanotechnology in food packaging: Pros and cons. *Journal of Agriculture and Food Research*, 7, Article 100270. https://doi.org/10.1016/j.jafr.2022.100270

[115] Lihui, Y., Chu, X., Wu, Y., Wang, Z., Liao, Z., Ji, X., Ju, J., Yang, B., Chen, Z., Dahlgren, R., Zhang, M., & Shang, X. (2024). Micro- and nano-plastics in the atmosphere: A review of occurrence, properties and human health risks. *Journal of Hazardous Materials*, 465, Article 133412. https://doi.org/10.1016/j.jhazmat.2023.133412

[116] Roman, M. (2015). Toxicity of cellulose nanocrystals: A review. *Industrial Biotechnology*,11(1), 25–33. https://doi.org/10.1089/ind.2014.0024

[117] Athinarayanan, J., Periasamy, V. S., & Alshatwi, A. A. (2020). Biocompatibility analysis of rice husk-derived silica nanoparticles for biomedical applications. *Ceramics International*, 46(8), 11982–11989. https://doi.org/10.1016/j.ceramint.2020.01.239

[118] Akter, M., Sikder, M. T., Rahman, M. M., Ullah, A. K. M. A., Hossain, K. F. B., Banik, S., & Saito, T. (2018). A systematic review on silver nanoparticles-induced cytotoxicity: Physicochemical properties and perspectives. *Journal of Advanced Research*, 9, 1–16. https://doi.org/10.1016/j.jare.2017.10.008

[119] Pikula, K., Johari, S. A., Santos-Oliveira, R. & Golokhvast, K. (2024). Joint toxicity and interaction of carbon-based nanomaterials with co-existing pollutants in aquatic environments: A review. *International Journal of Molecular Sciences*, 25*(21), 11798.* https://doi.org/10.3390/ijms252111798

[120] Safiki, A., Moses, M., & Musa, M. (2024). Application of green agricultural-based nanoparticles in cement-based construction materials: A systematic review. *Journal of Building Engineering*, 87, Article 108955. https://doi.org/10.1016/j.jobe.2024.108955

[121] Zhang, L., Forgham, H., Shen, A., Wang, J., Zhu, J., Huang, X., Tang, S., Xu, C., Davis, T.P., & Qiao, R. (2022). Nanomaterial integrated 3D printing for biomedical applications. *Journal of materials chemistry*. B. https://doi.org/10.1039/d2tb00931e

[122] Karsoun, A., Tolba, M., Abd El Aziz, A., Hassanin, A.M., Wahby, A., Klingner, A., & Tolba, K. (2023). Recycling Agriculture Waste for Liquid Deposition 3D Printing. 2023 2nd International Conference on Smart Cities 4.0, 258-263. https://doi.org/10.1109/SmartCities4.056956.2023.10525712

[123] Pemas, S., Gkiliopoulos, D., Samiotaki, C., Bikiaris, D. N., Terzopoulou, Z., & Pechlivani, E. M. (2024). Valorization of tomato agricultural waste for 3D-printed polymer composites based on poly (lactic acid). *Polymers,* 16(11), 1536. https://doi.org/10.3390/polym16111536

[124] Rahman, A. M., Rahman, T. T., Pei, Z., Ufodike, C. O., Lee, J., & Elwany, A. (2023). Additive manufacturing using agriculturally derived biowastes: A systematic literature review. *Bioengineering*, 10(7), 845. https://doi.org/10.3390/bioengineering10070845

[125] Wajid, M., Farooq, U., Alshammari, A., Alharbi, M. S., Almubaddal, M. S., Alhamami, M. A. M., & Khan, M. K. A. (2025). Interaction of nanomaterials with plants: Effects on growth, uptake, and stress response. *Plant Stress*, 13, Article 100512. https://doi.org/10.1016/j.plants.2024.100512

[126] Yan, Jipeng, Oyedeji, Oluwafemi, Leal, Juan H., Donohoe, Bryon S., Semelsberger, Troy A., Li, Chenlin, Hoover, Amber N., Webb, Erin, Bose, Elizabeth A., Zeng, Yining, Williams, C. Luke, Schaller, Kastli D., Sun, Ning, Ray, Allison E., & Tanjore, Deepti (2020). Characterizing Variability in Lignocellulosic Biomass: A Review. *ACS Sustainable Chemistry & Engineering,* 8(22). https://doi.org/10.1021/acssuschemeng.9b06263

[127] Dehua, X., Liu, Y., Song, M., & Zhou, J. (2024). Pulmonary toxicity and mechanisms induced by cellulose nanomaterials. *Journal of Nanobiotechnology*, 22(1), Article 759. https://doi.org/10.1186/s12951-024-02978-6

[128] Vidya, P. V., & Chitra, K. C. (2018). Evaluation of genetic damage in exposed to selected nanoparticles by using micronucleus and comet bioassays. *Croatian Journal of Fisheries*, 76(3), 115–124. https://doi.org/10.2478/cjf-2018-0014