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Advancements in Crystallogens Nanoparticles Fabricated by Agricultural Wastes

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Abstract

Using nanotechnology in agriculture has become a game-changing strategy to improve soil health, crop yield, and sustainability. This article investigates the production and uses of several nanoparticles obtained from agricultural wastes, such as those based on carbon, silicon, and lead. Carbon nanoparticles are created by processes such chemical vapor deposition, pyrolysis, and hydrothermal synthesis. They are valued for their large surface area, mechanical strength, and electrical conductivity. The nutrient cycle, water retention, and soil structure are all markedly enhanced by these nanoparticles. Synthesized from plentiful agricultural leftovers, silicon nanoparticles offer an affordable means of creating green fertilizers and boosting plant growth. Many studies have been done on their synthesis using chemical, physical, and environmentally friendly approaches. This article highlights the potential and challenges of utilizing nanotechnology in agriculture, emphasizing the importance of sustainable synthesis methods. The development of efficient nanoparticle production techniques from agricultural wastes offers innovative solutions to agricultural challenges, promoting a sustainable and resilient agricultural system.

Keywords: Nanomedicine, sustainable solutions, waste management

1. Introduction

Agricultural wastes are defined as the leftover plant residues that remain after the primary crop has been harvested. These wastes include a variety of materials such as leaves, stems, husks, roots, branches, and other organic components that are discarded or not used directly in the production process.

Globally, the accumulation of such waste is significant, with agricultural by-products forming one of the largest sources of organic waste. For instance, in the European Union alone, around 700 million tons of agricultural waste are generated annually, reflecting a considerable environmental challenge (Yearbook, 2013; Fritsch et al., 2017; Wikipedia contributors…, 2024; Mohite et al., 2022).

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In recent years, nanotechnology has emerged as a powerful tool for addressing environmental and waste management challenges. Nanotechnology refers to the manipulation of materials at the atomic or molecular scale, typically below 100 nanometers, leading to the creation of nanoparticles. These particles possess unique properties such as enhanced chemical reactivity, increased surface area, and novel optical or electrical behaviors. The integration of nanotechnology with green chemistry has opened new avenues for environmentally friendly agricultural waste management. Green chemistry emphasizes the design of chemical processes that minimize the use and generation of hazardous substances, making it a key player in sustainable waste recycling (Madhumitha, 2013).

Agricultural waste, or agro-waste, is composed of a variety of organic substances, mainly cellulose, hemicellulose, and lignin. In addition, some waste may contain proteins, oils, and other bioactive compounds. Agro-processing wastes include the remains of crops like rice, wheat, sugarcane, corn, and vegetables. For example, rice bran, which is a by-product of rice milling, has been extensively studied as a potential source for bioethanol production. Beyond plant waste, livestock waste, including animal manure such as cow dung, also constitutes a significant portion of agricultural waste. These organic residues are rich in essential nutrients and carbon, making them valuable for recycling into biofuels, fertilizers, and more recently, for use in the production of nanoparticles.

This review focuses on the utilization of agricultural waste in the synthesis of nanoparticles, particularly crystallogen-based nanoparticles. Crystallogens are elements from Group 14 of the periodic table, comprising carbon, silicon, germanium, tin, and lead. These elements exhibit versatile chemical behaviors, making them ideal candidates for nanoparticle synthesis. Nanoparticles of crystallogens have attracted considerable attention for their diverse applications, ranging from medicine to environ-mental remediation. For instance, carbon-based nanoparticles, such as carbon-coated metals, are extensively used in catalysis and energy storage. Silicon nanoparticles (SiNPs), on the other hand, are employed in the semiconductor industry and for biomedical imaging. In this review, we will explore the green synthesis methods used to produce these nanoparticles and their applications in various fields, including agriculture, medicine, and environmental monitoring. Nanoparticles synthesized from agro-waste present a dual benefit: reducing environmental pollution caused by waste accumulation and providing a sustainable source of nanomaterials. Moreover, metals like silver, gold, and zinc are used in combination with agro-waste to create nanoparticles that exhibit strong antimicrobial properties, enhancing their potential use in fields such as medicine, agriculture (as pesticides), and environmental monitoring. This integration of waste management and nanotechnology offers an innovative approach to addressing some of the most pressing global challenges (Figure 1).

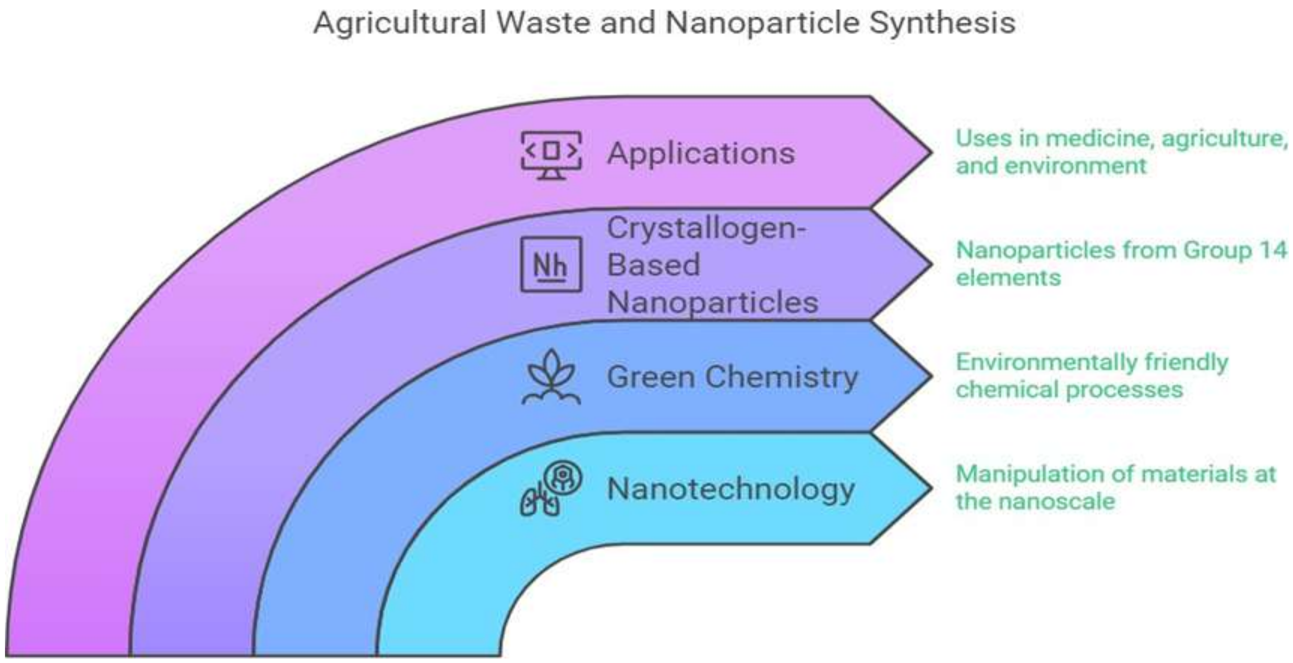

Fig. 1. Scientific representation of agricultural waste and nanotechnology integration.

2. Results and discussion

Methods for Nanoparticles Synthesis

The production, functionalization, and uses of metallic, semiconductor, magnetic, and multifunctional nanoparticles are the main topics of this area. This study is not intended to be a comprehensive compilation of all the literature; rather, we provide common and illustrative examples to facilitate discussions on the synthesis, functionalization, and uses of those nanoparticles. To guarantee the manufacturing of environmentally friendly nanoparticles, each method's sustainability and environmental impact must be carefully considered. The method of choosing is determined by the intended use and desired attributes of the nanoparticles.

Chemical Reduction

Chemical reduction is one of the most preferred methods for synthesizing nanoparticles due to its simplicity, cost-effectiveness, efficiency, and the ability to control structural parameters. This method is widely used because it is easy to perform and is one of the simplest approaches for nanoparticle synthesis (Szczyglewska et al., 2023).

In this method, substrates can be either natural compounds or chemicals, facilitating a reduction reaction. The oxidation or reduction states of the substrates can vary, allowing for diverse applications. The size of the nanoparticles plays a critical role in this process, as controlling the size enables the synthesis of nanoparticles with different morphologies.

The cost-effectiveness of the chemical reduction method makes it suitable for scaling up to large-scale preparation without the need for high pressure, energy, or temperature conditions. This scalability, combined with its simplicity, ensures its continued relevance in nanoparticle synthesis (Goia, 1998; Figure 2).

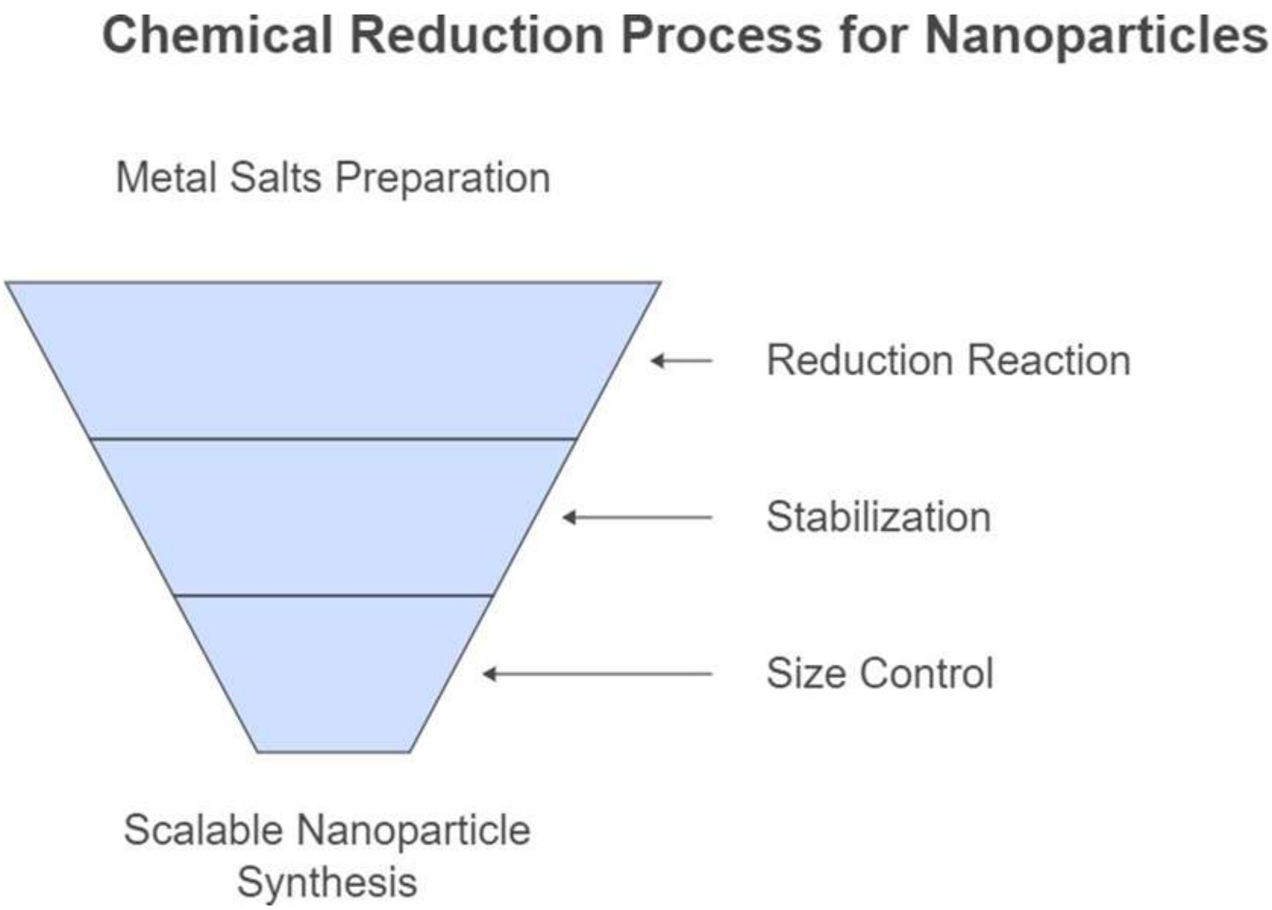

Fig. 2. Schematic representation of the chemical reduction process for synthesizing metal nanoparticles

Using a reducing agent and a stabilizer, salts of a chosen metal are reduced to create metal nanoparticles through chemical reduction (Sharma et al., 2019). The study by Chou and colleagues

(Chou, Ren, 2000) examined the use of silver nitrate in the chemical reduction process to create silver nanoparticles. ($AgNO_3$) as a metal precursor, formaldehyde (CH_2O) as a reducing agent, and polyvinylpyrrolidone/poly (vinyl alcohol), (PVP/PVA) as stabilizing agents. A solution of either sodium carbonate (Na_2CO_3) or sodium hydroxide (NaOH) The ideal pH was ascertained using sodium hydroxide (NaOH). It was investigated how the amount of alkaline solution affected the final nanoparticles shape.

Silver nitrate ($AgNO_3$) and other aqueous salts of metals can be chemically reduced to create zero-valent nanoparticles through a wet-chemical process known as chemical reduction. In order to reduce the precursor metal salt, metal ions must be reduced to zero valence by producing electrons for them by the employment of at least one reducing agent. Reductants including ascorbate, citrate, and borohydride are frequently utilized. A stabilizing agent stabilizes reduced nanoparticles. Cetyltrimethylammonium bromide [($C_{16}H_{33}$)N(CH_3)$_3$Br; CTAB], which is frequently employed in the manufacture of gold nanoparticles, is an illustration of a stabilizing agent. When creating silver nanoparticles, sodium citrate is one example of a reducing agent that can also serve as a stabilizing agent (Aashritha, 2013; Saleh, Alaqad, 2016).

Coprecipitation Method

Several people consider the coprecipitation method to be a standard method for creating magnetic nanoparticles (MNPs) because of its ease of use and efficiency (Guleri et al., 2020; Parmanik et al., 2022; Arsalani et al., 2019). In this chemical process, homogenous solutions containing the ions to be precipitated are combined. Precipitation happens when the target salt's solubility product is surpassed. When a substance's concentration reaches supersaturation during the coprecipitation process, nucleation usually starts suddenly. As more material diffuses onto the surface, nucleation grows and eventually forms nanoparticles. The rate of nucleation in relation to the growth phase needs to be carefully regulated in order to produce homogenous nanoparticles.

Fe_3O_4 nanoparticles are commonly synthesized using this method. A black pre capitate forms when NH4OH is added to a vigorously stirred mixture of $FeCl_2$ and $FeCl_3$ salts, maintaining a Fe^{2+} to Fe^{3+} 1:2 molar ratio at 70°C. After purification, the nanoparticles are collected via magnetic separation and repeatedly washed with ethanol and distilled water to remove residual chemicals (Arsalani et al., 2019; Qu et al., 2013; Dung et al., 2016; Khalil, 2015; Mascolo et al., 2013). Notably, the pH and ion concentration of the solution can influence the size of the resulting nanoparticles.

Despite its widespread use, little is known about the chemical pathways that result in the creation of the magnetite phase in the coprecipitation reaction. Optimizing the control over the crystal structure, morphology, and particle size of magnetite nanoparticles which are widely employed in biological applications requires an understanding of these processes (Ahn et al., 2012).

Microemulsion and Inverse Microemulsion Methods

Another popular method for creating nanoparticles is the use of microemulsion techniques, which take use of the particles' regulated sizes and shapes. An isotropic and thermodynamically stable mixture of water, oil, and surfactants often in combination with cosurfactants is called a microemulsion (Mittal, 2015). These systems serve as soft templates, providing a mildly regulated environment for the creation of nanoparticles.

Microemulsions can be classified into two main types: direct (oil dispersed in water) and reverse (water dispersed in oil). In the reverse microemulsion system, small aqueous-phase droplets (micelles) containing salts or other reactants are stabilized by surfactants in an oil matrix. Nanoparticle formation occurs when these micelles collide and mix, with the surfactant layer controlling the growth of nanoparticles (L´opez-Quintela, Rivas, 1993). For instance, Fe_3O_4 nanoparticles can be synthesized and further functionalized with a silica layer for enhanced stability and biocompatibility. This method is also used to prepare core shell structures, such as Fe_3O_4/Au nanoparticles, which prevent oxidation and enhance functionality (Feltin, Pileni, 1997).

The capacity to produce multifunctional nanoparticles makes the inverse microemulsion technique very noteworthy. Single nanoparticles are encapsulated within silica matrices that are created in the aqueous phase during this process (Dung et al., 2016). Numerous sectors, such as wound healing, oncology, cosmetology, and the creation of antiviral and antibacterial drugs, heavily rely on microemulsions (Nikolaev et al., 2023). These systems' thermodynamic stability permits uniform droplet production, and their stability is determined by molecular interactions within nanodomains.

Hydrothermal Method

Since its first use in geological study in the middle of the 19th century, the hydrothermal process has grown to become a commonly used technique for creating nanoparticles. With this technique, high-temperature and high-pressure conditions are created while reactions are carried out in an aqueous solution inside a closed reaction vessel. Substances that are normally insoluble or slightly soluble dissolve and recrystallize in these conditions (Yang, Park, 2019). Byrappa and Yoshimura (2007) state that the hydrothermal approach uses heterogeneous reactions at high pressures and temperatures to help create nanoparticles from insoluble chemicals. Usually, the procedure takes place in an autoclave, which is a steel pressure vessel that is filled with water and the required reactants. In general, hydrothermal synthesis doesn't require temperatures higher than 300°C. Supersaturation and increased reaction rates under these conditions promote the formation of nanoparticles.

Metal oxide nanoparticles, metal nanoparticles, and semiconductor nanoparticles have all been produced using this method extensively. For instance, the hydrothermal approach is frequently used to create carbon quantum dots (CQDs) with a consistent size distribution and a variety of surface functionalization (such as oxygen, nitrogen, or sulfur groups) (Li et al., 2011; Liu et al., 2018; Wang et al., 2018). Furthermore, metal oxide nanoparticles have been created under supercritical water conditions (Hayashi, Hakuta, 2010), and this method has also been successfully utilized to make metal (Kim et al., 2014) and semiconductor nanoparticles (Van Bui et al., 2014).

The hydrothermal method is a preferred technique in the synthesis of advanced materials because of its versatility and capacity to yield high-quality nanoparticles. This method is very much provided in the described type in the Figure 3 below.

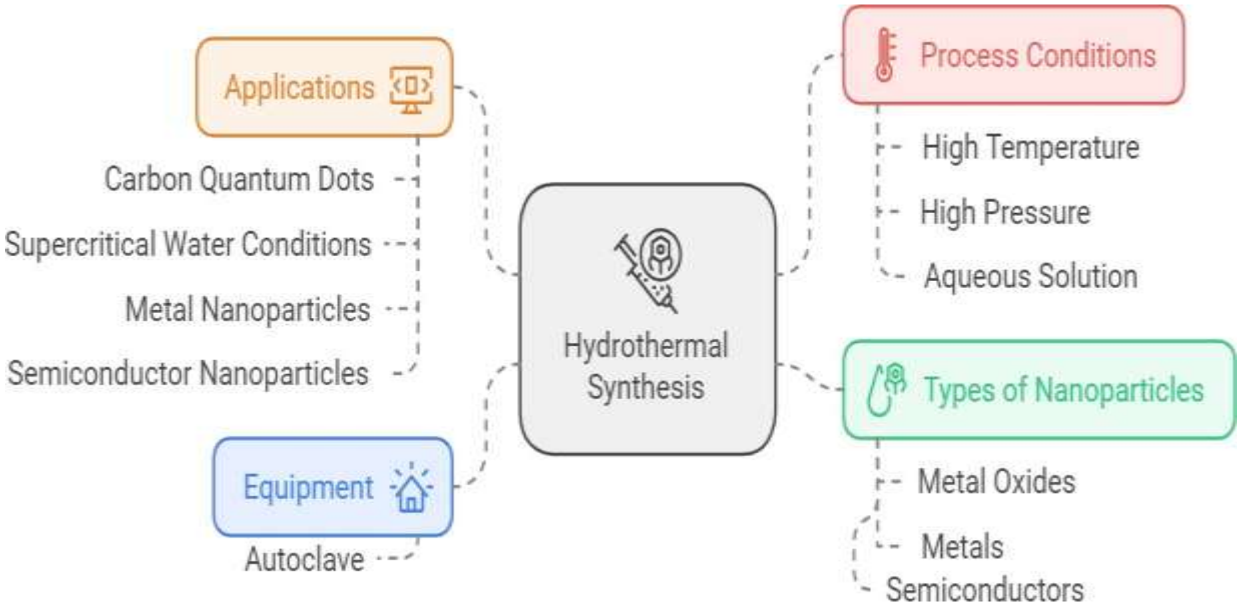

Fig. 3. Overview of Hydrothermal Synthesis: Applications, Process Conditions, Equipment, and Nanoparticle Types

Carbon Based Nanoparticles

Carbon is the very first element of the crystallogens. The usage of carbon in the agricultural industry extends far beyond basic applications. Carbon is essential due to its role in the photosynthetic process where plants use sunlight and air to release oxygen. It serves as nutrition for other animals and as a free energy source for soil microbial processes found in nature. The energy from plants and animals that we consume provides nourishment for soil microbes that supply plants with nutrients. It is present in plant roots, which give soil bacteria sustenance and help prevent soil erosion by giving regenerating soils structure.

Carbon accelerates the process by which nutrients are cycled back to young plants and is a major component of microbial glues that create soil structure, crucial for soil resilience. Additionally, it enhances water infiltration and water retention capacity (South Dakota..., 2024).

Carbon-based nanoparticles have gained significant importance over the last few decades. The discovery of Buckminster (C60) fullerenes in 1985 opened a new class of carbon chains which can be synthesized and produced. This class includes fullerenes, nano-onions, nano-cones, nano-horns, carbon dots, and carbon nanotubes (CNTs) (Mukherjee et al., 2016). Carbon nanoparticles are distinguished from regular carbon materials by their remarkable surface area, mechanical strength, electrical conductivity, low toxicity, biocompatibility, and thermal stability (Thippeswamy et al., 2021).

Many synthetic processes prepare carbon nanomaterials in different sizes, shapes, and chemical compositions. Chemical vapor deposition (CVD), which employs expensive ingredients like ethylene and carbon monoxide, is a common commercial process for producing carbon nanoparticles (CNPs) (Rajput et al., 2015; Zhao et al., 2020). CVD is the most used technique for the production of carbon nanotubes due to its lower temperature requirement, making the process more cost-effective compared to other methods. Additionally, CVD allows for control over the morphology and structure of the produced nanotubes (Manawi et al., 2018) making it a suitable candidate compared to earlier techniques like laser ablation (Guo et al., 1995) and electric arc discharge, both of which involve relatively higher temperatures (Journet et al., 1997).

Despite its effectiveness, CVD is not green and causes significant pollution due to the use of ethylene and carbon monoxide vapors, making the technique expensive. Therefore, carbon nanoparticles are now being synthesized from various agricultural wastes. For example, nitrogen-based carbon nanoparticles have demonstrated metal free electrocatalytic and glucose sensing activity (Li et al., 2015). Similar electrochemical sensors were observed when onion peel extract was used (Akshaya et al., 2019).

As for animal wastes, cow dung has been used to produce eco-friendly, cost-effective conductive paint (CP) (Bhakare et al., 2020). The wide range of applications of carbon-based nanoparticles can be attributed to the ability of carbon nanomaterials to form very strong bonds with objects lighter than them or with themselves. Carbon black or nanospheres derived from waste extract are used as nanofilters in different polymer matrices (Pace, 2001). Recent trends indicate that pyrolysis methods are gaining significant importance in carbon nanoparticle formation (Lee et al., 2017; Wibowo et al., 2015). This method uses a mixture of carbon dioxide along with methane and hydrogen. Agricultural wastes are reduced in size and subjected to high temperatures of about 500°C (Alaya et al., 2000; Jirimali et al., 2022).

Another method used for nanoparticle formation is hydrothermal synthesis, which converts agricultural wastes to fuels and carbon-based nanomaterials (Sharma et al., 2020). For example, collected samples of banana peels are placed in a hydrothermal reactor for 6 hours, where three major steps occur: material dehydration to produce furfural derivatives, followed by polymerization of the modified product, and finally, dehydration. The obtained product is then centrifuged to obtain banana peel carbon (Allwar et al., 2018).

The methods of preparation of various agricultural wastes are summarized in Table 1.

Table 1. Nanocarbon Production Methods from Various Agricultural Wastes

Agricultural Waste	Raw Material Preparation	Method	References
Pineapple Solid Biomass	Rinsed with hot deionized water, dried at 110 °C, cut into small pieces	Activated with zinc chloride, dried at 100°C, carbonized at500 °C	Nizamuddin et al., 2019; Mahamad et al., 2015
Pineapple Crown	Rinsed with deionized water, dried in sunlight, pre-carbonized at 50-250 °C	Activated with potassium hydroxide, pyrolyzed at 30-500 °C under inert atmosphere	Taer, Taslim, 2018; Taer et al., 2019
Rice Husk	Washed with distilled water, dried at 65 °C, ground into fine powder	Activated with ferrocene and ethanol, microwaved at 600 W, carbonized at 800-900 °C	Asnawi et al., 2018; Liou, 2004; Raman et al., 2017

Agricultural Waste	Raw Material Preparation	Method	References
Date Palm	Cleaned with deionized water, dried at 100-110 °C	Activated with an activator, boiled at 600-800 °C under N2 atmosphere	Hussein et al., 2015
Nicotiana Tabacum Stems	Cut into small pieces, dried at 105°C, impregnated with KOH	Carbonized,in muffle furnace under inert atmosphere, rinsed with HCl, dried at 105 °C	Musuna-Garwe et al., 2018
Sugarcane Bagasse	Collected in fiber form, cut into small pieces, impregnated with reagent	Pyrolyzed at 600-1000°C using generated gases	Alves et al., 2012
Orange Peel	Collected, activated with KOH, pyrolyzed	Activated at 600-800°C, K_2CO_3 decomposed, reacted to form hollow channels	Ranaweera et al., 2017

Silicon Nanoparticles from Agricultural Waste

Silicon is the 2nd element of group 14 of periodic table. When given as a fertilizer to certain soils, silicon is advantageous to a wide variety of crops. Although horsetail (Equisetum) and certain forms of algae require silicon from the environment to survive, most plants do not consider it to be an essential ingredient. Many plant species, particularly grasses, are able to absorb silicon at levels similar to those of macronutrients. The plant's high silicon concentration enhances its mechanical strength. In addition to its structural function, silicon can strengthen a plant's defensive mechanism against disease, pests, and environmental stress. Fertilizing soils with silicon boosts crop yields for certain crops, even in the absence of disease and under ideal growth conditions (Rutgers New…, 2018).

Silicon nanoparticles can be synthesied in both highly acidic and basic conditions by using quaternary alkylammonium surfactants, pluronic F127, P123 respectively (Beck et al., 1992; Kresge et al., 1992; Huo et al., 1994). The non-porous silica naroparticles core chemically synthesized by thermal method in which silicais burnt to form SiO_2 molecules. This method is also known as Aersol method (Panas et al., 2014; Mebert et al., 2017). On the other hand, another method called precipitation method is no adopted when an alkali-metal silicate (Rasmussen et al., 2013). Agricultural wastes have a high core of silicon content.

Crop residue like Grrain Cheff, Sugar Molasses and coconut hulls are presently being employed in the silicon nanoparticle synthesis. Water pollution is presently a topic of global concern can be addressed by the production of silicon nanoparticles (Akhayere et al., 2022; Shinde et al., 2021).

Agricultural Waste

Products from agriculture waste are used as fuel, to make green fertilizers, and occasionally to extract useful compounds. The production of SiNPs uses the agricultural waste as a precursor. Utilizing agricultural waste has several benefits, the primary one being its plentiful supply at the conclusion of each harvest season. Therefore, as compared to other approaches, nanoparticle production techniques that make use of agricultural wastes are always more cost-effective.

One agricultural waste product that contains large amounts of silica is rice husk. The usage of this material to create high-quality SiNPs has been the subject of numerous reports in the literature. For example, silica micro- and nanoparticles were first produced using rice hull by Jansomboon et al. (2017), Lu et al. (2024) manufactured very pure amorphous silica nanodiscs using rice straw as a source of silica. SiNPs were made from sugarcane bagasse, a significant waste product from the sugar industry. This environment friendly method provides an affordable means of utilizing agricultural waste. Seoka et al. created SiNPs and nano-silicon via magnesiothermic processes and SUGARCANE bagasse ash (Seroka et al., 2022). Using sticky, red, and brown rice husk ash, Sankar et al. created biogenerated SiNPs using a basic scheme of silica nanoparticles (Sankar et al., 2016).

Other Agricultural Waste Sources

In order to extract 52-78 % silica from various agricultural wastes, such as rice husk, bamboo leaves, sugarcane bagasse, and groundnut shellused to synthesized SiNPs (Akhayere et al., 2022). Through the use of annelid bioprocessing, crystalline SiNPs from agricultural waste produced. After generating humus from these agro-wastes employing *Eisenia foetida* species, SiNPs were obtained by calcination and acid treatment (Esp´ındola-Gonzalez et al., 2010). Using sedge (*Carex riparia*), which generates a lot of agro-waste, an innovative way to synthesize silica nanoparticles were reported (Costa, Paranhos, 2020). Naidu et al. (Naidu et al., 2023) synthesized silica nanoparticles for the food industry using sorghum residues, which contain significant levels of silica.

Table 2. Silicon Nanoparticles Synthesized using Other Agricultural Waste Sources

Source	Method	Reference
Rice husk, bamboo leaves, sugarcane bagasse, groundnut shell	-	Akhayere et al., 2022
Eisenia foetida treated agrowastes	Calcination, acid treatment	Esp´ındola-Gonzalez et al., 2010
Carex riparia	-	Costa, Paranhos, 2020
Sorghum residues	-	Naidu et al., 2023

Tin Oxide Nanoparticles from Plant-Mediated Synthesis

Plant-mediated synthesis has become a sustainable and cost-effective alternative for synthesizing nanoparticles, offering significant advantages over traditional physico-chemical methods. These green approaches eliminate the need for toxic chemicals, high temperatures, and high-pressure conditions, providing naturally sourced reducing and stabilizing agents. Moreover, the plant extracts allow the large-scale production of stable, uniform nanoparticles.

Several studies have explored various plant species for the green synthesis of tin oxide (SnO_2) nanoparticles, producing NPs with different morphologies and sizes depending on the specific plant extract and reaction conditions. The general process involves dissolving a tin salt in the plant extract, followed by centrifugation, drying, and thermal treatment to obtain the final product. Several plant-mediated syntheses of SnO_2 NPs have been reported, highlighting their application in photocatalysis and antibacterial activity. Table 3 summarizes notable studies in the literature.

The green synthesis of SnO_2 NPs has been shown to result in varying nanoparticle sizes and morphologies, depending on the specific plant species and conditions used. For instance, *Aspalathus linearis* yielded quasi-spherical particles with sizes ranging from 2.5 to 11.4 nm, while *Aloe barbadensis miller* produced larger particles ranging from 50 to 100 nm (Diallo et al., 2016; Selvakumari et al., 2017; Haritha et al., 2016; Gowri et al., 2013).

Table 3. Plant-Mediated SnO_2 Nanoparticles Synthesis

Plant Species	Precursor	Size, nm	Application
Aspalathus linearis (Diallo et al., 2016)	$SnCl_4·5H_2O$	2.5–11.4	Antibacterial Photocatalytic
Camellia sinensis Selvakumari et al., 2017)	$SnCl_4·5H_2O$	5–30	Photocatalytic
Catunaregam spinosa (Haritha et al., 2016)	$SnCl_2·2H_2O$	47	Dye Degradation
Aloe barbadensis miller (Gowri et al., 2013)	$SnCl_2·2H_2O$	50–100	Antibacterial
Plectranthus amboinicus (Fu et al., 2015)	$SnCl_2·2H_2O$	63	Photocatalytic
Nyctanthes arbortristis (Rajiv Gandhi et al., 2012)	$SnCl_2·2H_2O$	2–8	Hydrolysis Capping

Plant Species	Precursor	Size, nm	Application
Psidium guajava (Kumar et al., 2018)	$SnCl_4 \cdot 5H_2O$	8–10	Dye Degradation
Calotropis gigantea (Bhosale et al., 2018)	$SnCl_4 \cdot 5H_2O$	30–40	Dye Degradation
Piper betle (Singh et al., 2018)	$SnCl_4 \cdot 5H_2O$	8.4	Selective Dye Degradation

Lead Nanoparticles in Agriculture

Lead, the heaviest element in Group 14, plays a critical role in agriculture due to its detrimental effects, such as inhibiting photosynthesis, disrupting water balance, and altering membrane permeability in plants. The uptake of lead by plants is influenced by factors including particle size, root exudation, and various physical and chemical processes (Nas, Ali, 2018). Lead exists in various forms, including lead monoxide (PbO), lead dioxide (PbO_2), and lead(III) oxide (Pb_2O_3), with PbO being the most extensively studied due to its widespread use in industries such as batteries, gas production, and as a catalyst in organic chemistry (Panas et al., 2014; Rangaraj, Venkatachalam, 2017; Alshatwi et al., 2015).

Lead nanoparticle synthesis can be achieved via three main approaches: chemical, physical, and green (biological) methods. Techniques such as chemical synthesis, calcination, sol-gel pyrolysis, thermal breakdown, chemical deposition, and microwave irradiation have recently been developed to produce PbO nanostructures (Bratovcic, 2020). Bio-synthesis is particularly promising as it may enhance the properties of PbO nanoparticles while reducing the production of toxic by-products during synthesis (Rokade et al., 2016; Sharar, Bozeya, 2017). This method could offer an environmentally friendly alternative to traditional approaches for creating metal oxide nanoparticles.

Despite the significant potential of lead oxide nanoparticles, the environmental impact of PbO pollution remains a major concern. Lead oxide's substantial negative influence on ecosystems necessitates the development of effective solutions for managing lead pollution. Nanotechnology and biosynthesis may offer solutions by creating safer forms of lead nanoparticles. Recent research demonstrates that biosynthesis, including the use of natural gelatin-based stabilizers, can effectively produce PbO NPs, as discussed in recent work (Narayanan, 2012; Miri et al., 2018). However, the synthesis of PbO NPs from agro-waste remains an open area for further exploration.

Characterisation of NMs from Agro-Wastes

Value-added product production with minimal impact on the environment can be achieved by the production of nanomaterials (NMs) from agricultural waste. The abundance and renewable nature of agro-waste, which includes agricultural leftovers like fruit peels, rice husks, and sugarcane bagasse, make it a suitable feedstock for the synthesis of nanomaterials. To comprehend these NMs' physicochemical characteristics and possible uses, characterization is essential. With an emphasis on the structural, morphological, and functional characteristics of the nanomaterials made from agricultural waste, this section addresses the methods and procedures utilized to analyse them.

Fourier Transform Infrared Spectroscopy (FTIR)

By measuring the amount of absorbed energy and comparing it to a database, FTIR can be used to identify the functional groups that are present and characterize the chemical structure of the sample. FTIR spectroscopy is a very efficient and non-destructive method for analyzing the chemical and physical properties of lignocellulosic biomass (Guerrero-P´erez, Patience, 2020). Plant fiber is primarily composed of three components: cellulose, lignin, and hemicellulose. The literature has made considerable use of FTIR to verify the removal of amorphous sections such as hemicellulose and lignin from the fiber matrix following chemical treatments such as bleaching and alkali treatment, or to determine whether any lignin or hemicellulose is present in the extracted cellulose nanofibres. Chirayil et al. (2014) examined fibres that had been bleached, acid-treated, alkaline-treated, and left untreated using FTIR spectroscopy. They discovered a peak in each fiber's spectra at 3300 cm^1. The hydrophilic character of the fibers was shown by this peak, which matched the OH stretching vibrations of the hydrogen-bonded hydroxyl group.

According to Lima et al. (2023), FTIR analyses of the CNs produced from banana peel through enzymatic treatment yielded similar results. They were able to show that hemicellulose and lignin were successfully extracted from the fiber matrix by the enzymatic treatment. Bleaching was apparently used to remove the majority of the lignin in the banana peel cellulose nanofibres, according to Zope et al. (2022). Isolation The vibrations at 1238 per cm (guaiaryl ring respiration with stretching C=O), 1525 per cm (aromatic ring vibrations), and 761 per cm (C-H deformations) disappeared after bleaching. Karimi et al. (2014) examined the FTIR of samples of unbleached (UBNF) and bleached (BNF) kenaf bast cellulosic fiber and discovered that lignin was absent from both UBNF and BNF samples.

X-ray Photoelectron Spectroscopy (XPS)

XPS is a surface analysis technique that offers comprehensive insights into the chemical composition and states of a wide range of materials. Few XPS research have been conducted on cellulose nanofibres. Ahola et al. (2008) examined model films constructed of cellulose nano-fibrils using XPS in one study. They discovered that the surface was coated with cellulose nano-fibrils after spin-coating cellulose nano-fibril dispersions onto silica substrates to form these films.

In another work, the chemical composition of nano-fibrillated cellulose aerogels and films was examined by Zuo et al. (2019) both before and after coating them with a substance known as perfluorodecyl trichlorosilane (PFOTS). They discovered that carbon, oxygen, and trace levels of salt were present on the first cellulose surface. Following PFOTS coating, silicon, fluorine, were also present, indicating that PFOTS had interacted with the cellulose.

Measurements of the Zeta-Potential of Agriculture-Based NPs

The stability of suspensions containing cellulose nanofibers depends on the zeta potential. It gauges how much a liquid's particles oppose one another, keeping them uniformly distributed.

Dominic and colleagues' study (Dominic et al., 2022). They took measurements of the zeta potential of suspensions of banana peel-derived cellulose nanofibre (CN). With zeta potential values ranging from 16.2 to 44.2 mV, they produced extremely stable CN suspensions by subjecting the CNs to a high-pressure homogenizer many times. Surattanamal et al. (2022) found that the zeta potential of the nanofibers obtained by enzymatic and chemical treatment were respectively. They found that cellulose nanofibres with the greatest zeta capacity and higher electrical conductivity were generated via enzymatic therapy as opposed to chemical treatment.

Li and colleagues' study (2013), by measuring the water contact angles, they examined the hydrophilicity (the ability to repel water) of various starches. Additionally, they evaluated the zeta potential of starch granules and discovered that the values for rice, waxy maize, wheat, and potato starch were −20.5, −19.1, −20.4, and −4.2 mV, respectively. Wei and colleagues' study (2014), they noticed that the zeta potential dropped from −6.7 to −34.5 mV as the pH of the starch dispersion rose from 2.07 to 11.96. Furthermore, as the pH rose, the starch nanocrystal distribution widened.

Other Applications

Nano-Biosensors

NPs, plant fractions, soil, water, and nanotubes, nanowires, or nanocrystals in the agro-ecosystem are all monitored by NBSs. Using the physic-chemical properties of NMs, NBSs offer a potent tool compared to existing analytical sensors and biosensors that combine biological element detection with chemical or physical principles. Biological data is converted by a transducer into a signal that can be generated by an electrical device. With this skill, an agronomist may precisely and promptly keep an eye on the dietary and water requirements of the crops as well as any early indicators of illness (Mendes et al., 2020). For plant science research, high-resolution crop monitoring with nano-biosensors may be a highly helpful instrument.

Use of Nano-Fertilisers

Recent agricultural research has increasingly focused on micronutrients while some – what neglecting the critical role of macronutrients like nitrogen (N), phosphorus (P), and potassium (K) in influencing crop productivity. However, it's widely recognized that these macronutrients play a foundational role in supporting robust plant growth and yield. International and national organizations advocating for sustain- able agricultural practices and food security emphasize the importance of reorienting nanotechnology applications in agriculture towards developing nano-fertilizers specifically tailored to enhance the availability and efficiency of N and P. This shift aims to address pressing global challenges related to agricultural sustainability by ensuring that essential macronutrients are effectively utilized to meet growing food demands.

Nano-Fungicides

Fungi are mostly responsible for agricultural damage, including that to significant crops like rice, wheat, barley, groundnuts, and cotton (Neme, Mohammed, 2017). Fungicides can harm biodiversity, prompting the need for alternative strategies against fungal diseases. NPs, such as silver (Ag-NPs), copper (Cu-NPs), zinc oxide (ZnO-NPs), and magnesium oxide (MgO-NPs), have shown promising antifungal properties. Ag-NPs effectively reduce infections from fungi like *Magnaporthe grisea* and *Bipolaris sorokiniana*, while Cu-NPs and Ag-NPs inhibit *Alternaria alternata* and *Botrytis cinerea*. ZnO-NPs and MgO-NPs combat Rhizopus stolonifer, *Fusarium oxysporum*, and *Mucor plumbeus* (Bhattacharjee et al., 2022). Additionally, pesticides like zineb and mancozeb, when encapsulated in a MWCNT-g-PCA hybrid, demonstrate enhanced efficacy, with mancozeb particularly effective against *Alternaria alternata* (Nath et al., 2023).

3. Conclusion and Future Directions

The field of nanotechnology has demonstrated significant potential across various sectors, including agriculture, through the application of nanoparticles such as those based on carbon, silicon, and lead. Carbon-based nanoparticles, with their unique properties like high surface area, mechanical strength, and electrical conductivity, have enhanced soil structure, water retention, and nutrient cycling. Economical and environmentally friendly methods, such as chemical vapor deposition, pyrolysis, and hydrothermal synthesis, have been instrumental in their production, particularly from agricultural wastes. Silicon nanoparticles (SiNPs) derived from agricultural residues offer a sustainable and cost-effective solution for green fertilizers and plant growth enhancement. This approach not only addresses waste management challenges but also promotes sustainable agricultural practices. Similarly, while lead nanoparticles have been extensively studied for their industrial applications, their toxicological effects require further research to develop safe and effective uses in agriculture.

Looking ahead, the field of nanoparticle synthesis using biological organisms holds significant promise for future advancements. Research should explore novel microbial species from diverse and extreme environments, which may enable the synthesis of nanoparticles with unique properties. Genetic engineering and synthetic biology approaches can enhance the efficiency and specificity of nanoparticle synthesis, paving the way for engineered strains and custom-designed biosynthetic pathways. Mechanistic studies aimed at elucidating the molecular and biochemical processes involved in microbial nanoparticle synthesis will be vital for optimizing production methods and unlocking new biotechnological applications. Scaling up laboratory-scale synthesis to industrial production presents a critical challenge. Future research must focus on developing scalable, cost-effective processes for large-scale nanoparticle synthesis and integrating these processes into existing industrial frameworks. Furthermore, comprehensive studies on the environmental and health impacts of biologically synthesized nanoparticles are essential to ensure their safe and sustainable application. Long-term assessments of stability, biocompatibility, and toxicity will be crucial for mitigating risks and maximizing the benefits of nanotechnology. In conclusion, the integration of nanotechnology in agriculture and other industries offers immense opportunities for innovation and sustainability. Continued research and development, particularly in the areas of green synthesis and application of nanoparticles, will be essential to fully realize their potential while addressing associated challenges and ensuring safety for ecosystems and human health.

4. Declarations

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5. Author contribution

The study on silicon nanoparticles was done by Prachi Kurhade along with the section of characterisation was developed by her. Himanshu formulated the study on carbon nanoparticles and the application and Priyadrahsni Rajput and Sakshi Singh contributed in writing, editing and finalizing this work.

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References

Aashritha, 2013 – *Aashritha, S.* (2013). Synthesis of silver nanoparticles by chemical reduction method and their antifungal activity. *International Research Journal of Pharmacy*. 4(10).

Ahn et al., 2012 – *Ahn, T., Kim, J.H., Yang, H.-M., Lee, J.W., Kim, J.-D.* (2012). Formation pathways of magnetite nanoparticles by coprecipitation method. *The Journal of Physical Chemistry C*. 116(10): 6069-6076.

Ahola et al., 2008 – *Ahola, S., Salmi, J., Johansson, L.-S., Laine, J., Osterberg, M.* (2008). Model films from native cellulose nanofibrils. preparation, swelling, and surface interactions. *Biomacromolecules*. 9(4): 1273-1282.

Akhayere et al., 2022 – *Akhayere, E., Kavaz, D., Vaseashta, A.* (2022). Efficacy studies of silica nanoparticles synthesized using agricultural waste for mitigating waterborne contaminants. *Applied Sciences*. 12(18). DOI: https://doi.org/10.3390/app12189279.

Akhayere et al., 2022 – *Akhayere, E., Kavaz, D., Vaseashta, A.* (2022). Efficacy studies of silica nanoparticles synthesized using agricultural waste for mitigating waterborne contaminants. *Applied Sciences*. 12(18): 9279.

Akshaya et al., 2019 – *Akshaya, K., Bhat, V.S., Varghese, A., George, L., Hegde, G.* (2019). Non-enzymatic electrochemical determination of progesterone using carbon nanospheres from onion peels coated on carbon fiber paper. *Journal of the Electrochemical Society*. 166(13): 1097.

Alaya et al., 2000 – *Alaya, M., Girgis, B., Mourad, W.* (2000). Activated carbon from some agricultural wastes under action of one-step steam pyrolysis. *Journal of Porous Materials*. 7: 509-517.

Allwar et al., 2018 – *Allwar, A., Febriyantri, H.Z., Yuliantari, R.* (2018). Research article preparation and characterization of hydrothermal activated carbon from banana empty fruit bunch with ZnCl2 activation for removal of phenol in aqueous solution.

Alshatwi et al., 2015 – *Alshatwi, A.A., Athinarayanan, J., Periasamy, V.S.* (2015). Biocompatibility assessment of rice husk-derived biogenic silica nanoparticles for biomedical applications. *Materials Science and Engineering: C*. 47: 8-16.

Alves et al., 2012 – *Alves, J.O., Ten´orio, J.A.S., Zhuo, C., Levendis, Y.A.* (2012). Characterization of nanomaterials produced from sugarcane bagasse. *Journal of Materials Research and Technology*. 1(1): 31-34.

Arsalani et al., 2019 – *Arsalani, S., Guidelli, E.J., Silveira, M.A., Salmon, C.E., Araujo, J.F., Bruno, A.C., Baffa, O.* (2019). Magnetic Fe_3O_4 nanoparticles coated by natural rubber latex as MRI contrast agent. *Journal of Magnetism and Magnetic Materials*. 475: 458-464.

Asnawi et al., 2018 – *Asnawi, M., Azhari, S., Hamidon, M.N., Ismail, I., Helina, I.* (2018). Synthesis of carbon nanomaterials from rice husk via microwave oven. *Journal of Nanomaterials*. 2018(1): 2898326.

Beck et al., 1992 – *Beck, J.S., Vartuli, J.C., Roth, W.J., Leonowicz, M.E., Kresge, C.T., Schmitt, K.D., Chu, C.T., Olson, D.H., Sheppard, E.W., McCullen, S.B., et al.* (1992). A new family of mesoporous molecular sieves prepared with liquid crystal templates. *Journal of the American Chemical Society*. 114(27): 10834-10843.

Bhakare et al., 2020 – *Bhakare, M.A., Wadekar, P.H., Khose, R.V., Bondarde, M.P., Some, S.* (2020). Eco- friendly biowaste-derived graphitic carbon as black pigment for conductive paint. *Progress in Organic Coatings*. 147: 105872.

Bhattacharjee et al., 2022 – *Bhattacharjee, R., Kumar, L., Mukerjee, N., Anand, U., Dhasmana, A., Preetam, S., Bhaumik, S., Sihi, S., Pal, S., Khare, T. et al.* (2022). The emergence of metal oxide nanoparticles (NPs) as a phytomedicine: A two-facet role in plant growth, nano-toxicity and anti-phyto-microbial activity. *Biomedicine & Pharmacotherapy*. 155: 113658.

Bhosale et al., 2018 – *Bhosale, T., Shinde, H., Gavade, N., Babar, S., Gawade, V., Sabale, S., Kamble, R., Shirke, B., Garadkar, K.* (2018). Biosynthesis of SnO2 nanoparticles by aqueous leaf extract of *Calotropis gigantea* for photocatalytic applications. *Journal of Materials Science: Materials in Electronics*. 29: 6826-6834.

Bratovcic, 2020 – *Bratovcic, A.* (2020). Synthesis, characterization, applications, and toxicity of lead oxide nanoparticles. *Lead Chemistry*. 10.

Byrappa, Adschiri, 2007 – *Byrappa, K., Adschiri, T.* (2007). Hydrothermal technology for nanotechnology. *Progress in Crystal Growth and Characterization of Materials*. 53(2): 117-166.

Chirayil et al., 2014 – *Chirayil, C.J., Joy, J., Mathew, L., Mozetic, M., Koetz, J., Thomas, S.* (2014). Isolation and characterization of cellulose nanofibrils from *Helicteres isora* plant. *Industrial Crops and Products*. 59: 27-34.

Chou, Ren, 2000 – *Chou, K.S., Ren, C.Y.* (2000). Synthesis of nanosized silver particles by chemical reduction method. *Materials Chemistry and Physics*. 64(3): 241-246.

Costa, Paranhos, 2020 – *Costa, J.A.S., Paranhos, C.M.* (2020). Mitigation of silica-rich wastes: an alternative to the synthesis eco-friendly silica-based mesoporous materials. *Microporous and Mesoporous Materials*. 309: 110570.

Diallo et al., 2016 – *Diallo, A., Manikandan, E., Rajendran, V., Maaza, M.* (2016). Physical & enhanced photocatalytic properties of green synthesized SnO2 nanoparticles via *Aspalathus linearis*. *Journal of Alloys and Compounds*. 681: 561-570.

Dominic et al., 2022 – *Dominic, C.M., Raj, V., Neenu, K., Begum, P.S., Formela, K., Saeb, M.R., Prabhu, D.D., Vijayan, P.P., Ajithkumar, T., Parameswaranpillai, J.* (2022). Chlorine- free extraction and structural characterization of cellulose nanofibers from waste husk of millet (*Pennisetum glaucum*). *International Journal of Biological Macromolecules*. 206: 92-104.

Dung et al., 2016 – *Dung, C.T., Quynh, L.M., Linh, N.P., Nam, N.H., Luong, N.H.* (2016). Synthesis of ZnS: Mn–Fe_3O_4 bifunctional nanoparticles by inverse microemulsion method. Journal of Science. *Advanced Materials and Devices*. 1(2): 200-203.

Esp´ındola-Gonzalez et al., 2010 – *Esp´ındola-Gonzalez, A., Mart´ınez-Hern´andez, A., Angeles-Ch´avez, C., Castano, V., Velasco-Santos, C.* (2010). Novel crystalline SiO2 nanoparticles via annelids bio- processing of agro-industrial wastes. *Nanoscale Research Letters*. 5: 1408-1417.

Feltin, Pileni, 1997 – *Feltin, N., Pileni, M.* (1997). New technique for synthesizing iron ferrite magnetic nanosized particles. *Langmuir*. 13(15): 3927-3933.

Fritsch et al., 2017 – *Fritsch, C., Staebler, A., Happel, A., Cubero M´arquez, M.A., Aguil´o-Aguayo, I., Abadias, M., Gallur, M., Cigognini, I.M., Montanari, A., L´opez, M.J., et al.* (2017). Processing, valorization and application of bio-waste derived compounds from potato, tomato, olive and cereals: A review. *Sustainability*. 9(8): 1492.

Fu et al., 2015 – *Fu, L., Zheng, Y., Ren, Q., Wang, A., Deng, B.* (2015). Green biosynthesis of SnO2 nanoparticles by *Plectranthus amboinicus* leaf extract their photocatalytic activity toward rhodamine b degradation. *Journal of Ovonic Research*. 11(1): 21-26.

Goia, 1998 – *Goia, D.V., Matijevi´c, E.* (1998). Preparation of monodispersed metal particles. *New Journal of Chemistry*. 22(11): 1203-1215.

Gowri et al., 2013 – *Gowri, S., Gandhi, R.R., Sundrarajan, M.* (2013). Green synthesis of tin oxide nanoparticles by aloe vera: structural, optical and antibacterial properties. *Journal of Nanoelectronics and Optoelectronics*. 8(3): 240-249.

Guerrero-P´erez, Patience, 2020 – *Guerrero-P´erez, M.O., Patience, G.S.* (2020). Experimental methods in chemical engineering: Fourier transform infrared spectroscopy—FTIR. *The Canadian Journal of Chemical Engineering*. 98(1): 25-33.

Guleri et al., 2020 – *Guleri S., Singh, K., Kaushik, R., Dhankar, R., Tiwari, A.* (2020). Phycoremediation: a novel and synergistic approach in wastewater remediation. *Journal of Microbiology, Biotechnology and Food Sciences*. 10(1): 98-106.

Guo et al., 1995 – *Guo, T., Nikolaev, P., Thess, A., Colbert, D.T., Smalley, R.E.* (1995). Catalytic growth of single-walled nanotubes by laser vaporization. *Chemical Physics Letters*. 243(1-2): 49-54.

Haritha et al., 2016 – *Haritha, E., Roopan, S.M., Madhavi, G., Elango, G., Al-Dhabi, N.A., Arasu, M.V.* (2016). Green chemical approach towards the synthesis of SnO2 NPs in argument with photocatalytic degradation of diazo dye and its kinetic studies. *Journal of Photochemistry and Photobiology B: Biology*. 162: 441-447.

Hayashi, Hakuta, 2010 – *Hayashi, H., Hakuta, Y.* (2010). Hydrothermal synthesis of metal oxide nanoparticles in supercritical water. *Materials*. 3(7): 3794-3817.

Huo et al., 1994 – *Huo, Q., Margolese, D.I., Ciesla, U., Feng, P., Gier, T.E., Sieger, P., Leon, R., Petroff, P.M., Schuth, F., Stucky, G.D.* (1994). Generalized synthesis of periodic surfactant/inorganic composite materials. *Nature*. 368(6469): 317-321.

Hussein et al., 2015 – *Hussein, F.H., Halbus, A.F., Lafta, A.J., Athab, Z.H.* (2015). Preparation and characterization of activated carbon from Iraqi Khestawy date palm. *Journal of Chemistry*. 2015(1): 295748.

Jansomboon et al., 2017 – *Jansomboon, W., Boonmaloet, K., Sukaros, S., Prapainainar, P.* (2017). Rice hull micro and nanosilica: synthesis and characterization. *Key Engineering Materials*. 718: 77-80.

Jirimali et al., 2022 – *Jirimali, H., Singh, J., Boddula, R., Lee, J.K., Singh, V.* (2022). Nano-structured carbon: its synthesis from renewable agricultural sources and important applications. *Materials*. 15(11): 3969.

Journet et al., 1997 – *Journet, C., Maser, W.K., Bernier, P., Loiseau, A., La Chapelle, M.L., Lefrant, d.S., Deniard, P., Lee, R., Fischer, J.E.* (1997). Large-scale production of single-walled carbon nanotubes by the electric-arc technique. *Nature*. 388(6644): 756-758.

Karimi et al., 2014 – *Karimi, S., Tahir, P.M., Karimi, A., Dufresne, A., Abdulkhani, A.* (2014). Kenaf bast cellulosic fibers hierarchy: a comprehensive approach from micro to nano. *Carbohydrate Polymers*. 101: 878885.

Khalil, 2015 – *Khalil, M.I.* (2015). Co-precipitation in aqueous solution synthesis of magnetite nanoparticles using iron (iii) salts as precursors. *Arabian Journal of Chemistry*. 8(2): 279-284.

Kim et al., 2014 – *Kim, M., Son, W.-S., Ahn, K.H., Kim, D.S., Lee, H.-s., Lee, Y.-W.* (2014). Hydrothermal synthesis of metal nanoparticles using glycerol as a reducing agent. *The Journal of Supercritical Fluids*. 90: 53-59.

Kresge et al., 1992 – *Kresge, A.C., Leonowicz, M.E., Roth, W.J., Vartuli, J., Beck, J.* (1992). Ordered meso-porous molecular sieves synthesized by a liquid-crystal template mechanism. *Nature*. 359(6397): 710-712.

Kumar et al., 2018 – *Kumar, M., Mehta, A., Mishra, A., Singh, J., Rawat, M., Basu, S.* (2018). Biosynthesis of tin oxide nanoparticles using *Psidium guajava* leave extract for photocatalytic dye degradation under sunlight. *Materials Letters*. 215: 121-124.

L´opez-Quintela, Rivas, 1993 – *L´opez-Quintela, M.A., Rivas, J.* (1993). Chemical reactions in microemulsions: a powerful method to obtain ultrafine particles. *Journal of Colloid and Interface Science*. 158(2): 446-451.

Lee et al., 2017 – *Lee, J., Yang, X., Cho, S.-H., Kim, J.-K., Lee, S.S., Tsang, D.C., Ok, Y.S., Kwon, E.E.* (2017). Pyrolysis process of agricultural waste using CO2 for waste management, energy recovery, and biochar fabrication. *Applied Energy*. 185: 214-222.

Li et al., 2011 – *Li, H., He, X., Liu, Y., Huang, H., Lian, S., Lee, S.-T., Kang, Z.* (2011). One-step ultrasonic synthesis of water-soluble carbon nanoparticles with excellent photoluminescent properties. *Carbon*. 49(2): 605-609.

Li et al., 2013 – *Li, C., Li, Y., Sun, P., Yang, C.* (2013). Pickering emulsions stabilized by native starch granules. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 431: 142-149.

Li et al., 2015 – *Li, T., Li, Y., Wang, C., Gao, Z.D., Song, Y.Y.* (2015). Nitrogen-doped carbon nanospheres derived from cocoon silk as metal-free electrocatalyst for glucose sensing. *Talanta*. 144: 1245-1251.

Lima et al., 2023 – *Lima, A.R., Cristofoli, N.L., Costa, A.M.R., Saraiva, J.A., Vieira, M.C.* (2023). Comparative study of the production of cellulose nanofibers from agro-industrial waste streams of *Salicornia ramosissima* by acid and enzymatic treatment. *Food and Bioproducts Processing*. 137: 214-225.

Liou, 2004 – *Liou, T.-H.* (2004). Preparation and characterization of nano-structured silica from rice husk. *Materials Science and Engineering: A*. 364(1-2): 313-323.

Liu et al., 2018 – *Liu, J., Li, D., Zhang, K., Yang, M., Sun, H., Yang, B.* (2018). One-step hydrothermal synthesis of nitrogen-doped conjugated carbonized polymer dots with 31% efficient red emission for in vivo imaging. *Small*. 14(15): 1703919.

Lu et al., 2007 – *Lu, A.H., Salabas, E.E., Schu¨th, F.* (2007). Magnetic nanoparticles: synthesis, protection, functionalization, and application. *Angewandte Chemie International Edition*. 46(8): 1222-1244.

Lu et al., 2024 – *Lu, Y., Jiang, M., Pan, Y., Wang, F., Xu, W., Zhou, Y., Du, X.* (2024). Preparation of Ag@lignin nanotubes for the development of antimicrobial biodegradable films from corn straw. *International Journal of Biological Macromolecules*. 254: 127630.

Madhumitha, 2013 – *Madhumitha, G., Roopan, S.M.* (2013). Devastated crops: multifunctional efficacy for the production of nanoparticles. *Journal of Nanomaterials*. 1: 951858.

Mahamad et al., 2015 – *Mahamad, M.N., Zaini, M.A.A., Zakaria, Z.A.* (2015). Preparation and characterization of activated carbon from pineapple waste biomass for dye removal. *International Biodeterioration & Biodegradation*. 102: 274-280.

Manawi, et al., 2018 – *Manawi, Y.M., Ihsanullah, Samara, A., Al-Ansari, T., Atieh, M.A.* (2018). A review of carbon nanomaterials' synthesis via the chemical vapor deposition (CVD) method. *Materials*. 11(5): 822.

Mascolo et al., 2013 – *Mascolo, M.C., Pei, Y., Ring, T.A.* (2013). Room temperature co-precipitation synthesis of magnetite nanoparticles in a large pH window with different bases. *Materials*. 6(12): 5549-5567.

Mebert et al., 2017 – *Mebert, A.M., Baglole, C.J., Desimone, M.F., Maysinger, D.* (2017). Nanoengineered silica: Properties, applications and toxicity. *Food and Chemical Toxicology*. 109: 753-770.

Mendes et al., 2020 – *Mendes, J., Pinho, T.M., Santos, F., Sousa, J.J., Peres, E., Boaventura-Cunha, J., Cunha, M., Morais, R.* (2020). Smartphone applications targeting precision agriculture practices – a systematic review. *Agronomy*. 10(6): 855.

Miri et al., 2018 – *Miri, A., Sarani, M., Hashemzadeh, A., Mardani, Z., Darroudi, M.* (2018). Biosynthesis and cytotoxic activity of lead oxide nanoparticles. *Green Chemistry Letters and Reviews*. 11(4): 567-572.

Mittal, 2015 – *Mittal, V.* (2015). Synthesis Techniques for Polymer Nanocomposites. John Wiley & Sons.

Mohite et al., 2022 – *Mohite, A.S., Jagtap, A.R., Avhad, M.S., More, A.P.* (2022). Recycling of major agri- culture crop residues and its application in polymer industry: A review in the context of waste to energy nexus. *Energy Nexus*. 7: 100134.

Mukherjee et al., 2016 – *Mukherjee, A., Majumdar, S., Servin, A.D., Pagano, L., Dhankher, O.P., White, J.C.* (2016). Carbon nanomaterials in agriculture: a critical review. *Frontiers in Plant Science*. 7: 172.

Musuna-Garwe et al., 2018 – *Musuna-Garwe, C.C., Mukaratirwa-Muchanyereyi, N., Mupa, M., Mahamadi, C., Mujuru, M.* (2018). Preparation and characterization of nanocarbons from nicotiana tabacum stems. *AIMS Mater Sci*. 5: 1242-1254.

Naidu et al., 2023 – *Naidu, S., Pandey, J., Mishra, L.C., Chakraborty, A., Roy, A., Singh, I.K., Singh, A.* (2023). Silicon nanoparticles: Synthesis, uptake and their role in mitigation of biotic stress. *Ecotoxicology and Environmental Safety*. 255: 114783.

Narayanan, 2012 – *Narayanan, R.* (2012). Synthesis of green nanocatalysts and industrially important green reactions. *Green Chemistry Letters and Reviews*. 5(4): 707–725.

Nas, Ali, 2018 – *Nas, F.S., Ali, M.* (2018). The effect of lead on plants in terms of growing and biochemical parameters: a review. *MOJ Ecology & Environmental Sciences*. 3(4): 265-268.

Nath et al., 2023 – *Nath, P.C., Ojha, A., Debnath, S., Sharma, M., Sridhar, K., Nayak, P.K., Inbaraj, B.S.* (2023). Biogeneration of valuable nanomaterials from agro-wastes: A comprehensive review. *Agronomy*. 13(2): 561.

Neme, Mohammed, 2017 – *Neme, K., Mohammed, A.* (2017). Mycotoxin occurrence in grains and the role of postharvest management as mitigation strategies. A review. *Food Control*. 78: 412-425.

Nikolaev et al., 2023 – *Nikolaev, B., Yakovleva, L., Fedorov, V., Li, H., Gao, H., Shevtsov, M.* (2023). Nano-and microemulsions in biomedicine: From theory to practice. *Pharmaceutics*. 15(7): 1989.

Nizamuddin et al., 2019 – *Nizamuddin, S., Jadhav, A., Qureshi, S.S., Baloch, H.A., Siddiqui, M., Mubarak, N., Griffin, G., Madapusi, S., Tanksale, A., Ahamed, M.I.* (2019). Synthesis and characterization of polylactide/rice husk hydrochar composite. *Scientific Reports*. 9(1): 5445.

Pace, 2001 – *Pace, N.R.* (2001). The universal nature of biochemistry. *Proceedings of the National Academy of Sciences*. 98(3): 805-808.

Panas et al., 2014 – *Panas, A., Comouth, A., Saathoff, H., Leisner, T., Al-Rawi, M., Simon, M., Seemann, G., Dossel, O., Mulhopt, S., Paur, H.-R., et al.* (2014). Silica nanoparticles are less toxic to human lung cells when deposited at the air–liquid interface compared to conventional submerged exposure. *Beilstein Journal of Nanotechnology*. 5(1): 1590-1602.

Parmanik et al., 2022 – *Parmanik, A., Bose, A., Ghosh, B.* (2022). Research advancement on magnetic iron oxide nanoparticles and their potential biomedical applications. *Minerva Biotechnology & Biomolecular Research*. 34(2).

Qu et al., 2013 – *Qu, X., Brame, J., Li, Q., Alvarez, P.J.* (2013). Nanotechnology for a safe and sustainable water supply: enabling integrated water treatment and reuse. *Accounts of Chemical Research*. 46(3): 834-843.

Rajiv Gandhi et al., 2012 – *Rajiv Gandhi, R., Gowri, S., Suresh, J., Selvam, S., Sundrarajan, M*. (2012). Biosynthesis of tin oxide nanoparticles using corolla tube of *Nyctanthes arbor-tristis* flower extract. *Journal of Biobased Materials and Bioenergy*. 6(2): 204-208.

Rajput, 2015 – *Rajput, N.* (2015). Methods of preparation of nanoparticles-a review. *International Journal of Advances in Engineering & Technology*. 7(6): 1806.

Raman et al., 2017 – *Raman, S.M., Ismail, N.A., Jamari, S.S.* (2017). Preparation and characterization of impregnated commercial rice husks activated carbon with piperazine for carbon dioxide (CO2) capture. In: *IOP Conference Series: Materials Science and Engineering*. 206: 012005. IOP Publishing.

Ranaweera et al., 2017 – *Ranaweera, C., Kahol, P., Ghimire, M., Mishra, S., Gupta, R.K.* (2017). Orange-peel-derived carbon: designing sustainable and high-performance supercapacitor electrodes. *C*. 3(3): 25.

Rangaraj, Venkatachalam, 2017 – *Rangaraj, S., Venkatachalam, R*. (2017). A lucrative chemical processing of bamboo leaf biomass to synthesize biocompatible amorphous silica nanoparticles of biomedical importance. *Applied Nanoscience*. 7: 145-153.

Rasmussen et al., 2013 – *Rasmussen K, Mech A, Mast J, De Temmerman P, Waegeneers N, Van Steen F, Pizzolon J, De Temmerman L, Van Doren E, Jensen K, Birkedal R, Levin M, Nielsen S, Koponen I, Clausen P, Kembouche Y, Thieriet N, Spalla O, Giuot C, Rousset D, Witschger O, Bau S, Bianchi B, Shivachev B, Gilliland D, Pianella F, Ceccone G, Cotogno G, Rauscher H, Gibson P, Stamm H*. (2013). Synthetic Amorphous Silicon Dioxide (NM-200, NM-201, NM-202, NM-203, NM-204): Characterisation and Physico-Chemical Properties. EUR 26046. Luxembourg (Luxembourg): Publications Office of the European Union. JRC83506

Rokade et al., 2016 – *Rokade, A.A., Patil, M.P., Yoo, S.I., Lee, W.K., Park, S.S.* (2016). Pure green chemical approach for synthesis of Ag2O nanoparticles. *Green Chemistry Letters and Reviews*. 9(4): 216-222.

Rutgers New…, 2018 – Rutgers New Jersey Agricultural Experiment Station. Understanding Soil Microbes and Nutrient Recycling. 2018. [Electronic resource]. URL: https://njaes.rutgers.edu/fs1278

Saleh, Alaqad, 2016 – *Saleh, T., Alaqad, K.* (2016). Analytical toxicology gold and silver nanoparticles: Synthesis methods, characterization routes and applications towards drugs. *Journal of Environmental and Analytical Toxicology*. 6(4).

Sankar et al., 2016 – *Sankar, S., Sharma, S.K., Kaur, N., Lee, B., Kim, D.Y., Lee, S., Jung, H.* (2016). Bio- generated silica nanoparticles synthesized from sticky, red, and brown rice husk ashes by a chemical method. *Ceramics International*. 42(4): 4875-4885.

Selvakumari et al., 2017 – *Selvakumari, J.C., Ahila, M., Malligavathy, M., Padiyan, D.P.* (2017). Structural, morphological, and optical properties of tin(IV) oxide nanoparticles synthesized using *Camellia sinensis* extract: a green approach. *International Journal of Minerals, Metallurgy, and Materials*. 24: 1043-1051.

Seroka et al., 2022 – *Seroka, N.S., Taziwa, R.T., Khotseng, L. (2022)*. Extraction and synthesis of silicon nanoparticles (SiNPs) from sugarcane bagasse ash: a mini review. *Applied Sciences*. 12(5): 2310.

Sharar, Bozeya, 2017 – *Sharar, M., Bozeya, A.* (2017). Green Chem. Lett. Rev. 2017, 10: 3, 121; Naeimi, H., Babaei, Z. *Green Chem. Lett. Rev*. 10(3): 129.

Sharma et al., 2019 – *Sharma, G., Kumar, A., Sharma, S., Naushad, M., Dwivedi, R.P., ALOthman, Z.A., Mola, G.T.* (2019). Novel development of nanoparticles to bimetallic nanoparticles and their composites: A review. *Journal of King Saud University-Science*. 31(2): 257-269.

Sharma et al., 2020 – *Sharma, R., Jasrotia, K., Singh, N., Ghosh, P., Srivastava, S., Sharma, N.R., Singh, J., Kanwar, R., Kumar, A.* (2020). A comprehensive review on hydrothermal carbonization of biomass and its applications. *Chemistry Africa*. 3: 1-19.

Shinde et al., 2021 – *Shinde, P.S., Suryawanshi, P.S., Patil, K.K., Belekar, V.M., Sankpal, S.A., Delekar, S.D., Jadhav, S.A.* (2021). A brief overview of recent progress in porous silica as catalyst supports. *Journal of Composites Science*. 5(3). DOI: https://doi.org/10.3390/jcs5030075.

Singh et al., 2018 – *Singh, J., Kaur, N., Kaur, P., Kaur, S., Kaur, J., Kukkar, P., Kumar, V., Kukkar, D., Rawat, M.* (2018). Piper betle leaves mediated synthesis of biogenic SnO2 nanoparticles for photocatalytic degradation of reactive yellow 186 dye under direct sunlight. *Environmental Nanotechnology, Monitoring & Management*. 10: 331-338.

South Dakota..., 2024 – South Dakota State University Extension Why Carbon is So Important to Agriculture and Society. 2024. [Electronic resource]. URL: https://extension.sdstate.edu/why-carbon-so-important-agriculture-and-society (date of access: 15.07.2024).

Surattanamal et al., 2022 – *Surattanamal, F., Sulong, S., Waloh, N., Sohsansa, B., Dahlan, W., Suksuwan, A.* (2022). Physicochemical properties of cellulose extracted from hom thong banana peels. In: *Proceedings of The International Halal Science and Technology Conference*. 14: 194-201.

Szczyglewska et al., 2023 – *Szczyglewska, P., Feliczak-Guzik, A., Nowak, I.* (2023). Nanotechnology–general aspects: A chemical reduction approach to the synthesis of nanoparticles. *Molecules*. 28(13): 4932.

Taer et al., 2019 – *Taer, E., Apriwandi, A., Ningsih, Y., Taslim, R., et al.* (2019). Preparation of activated carbon electrode from pineapple crown waste for supercapacitor application. *International Journal of Electrochemical Science*. 14(3): 2462-2475.

Taer, Taslim, 2018 – *Taer, E., Taslim, R.* (2018). Brief review: Preparation techniques of biomass based activated carbon monolith electrode for supercapacitor applications. In: *AIP Conference Proceedings*. vol. 1927. AIP Publishing.

Thippeswamy et al., 2021 – *Thippeswamy, B.H., Maligi, A.S., Hegde, G.* (2021). Roadmap of effects of biowaste-synthesized carbon nanomaterials on carbon nano-reinforced composites. *Catalysts*. 11(12): 1485.

Van Bui et al., 2014 – *Van Bui, H., Nguyen, H.N., Hoang, N.N., Truong, T.T., Pham, V.B.* (2014). Optical and magnetic properties of Mn-doped ZnS nanoparticles synthesized by a hydrothermal method. *IEEE Transactions on Magnetics*. 50(6): 1-4.

Wang et al., 2018 – *Wang, G., Guo, Q., Chen, D., Liu, Z., Zheng, X., Xu, A., Yang, S., Ding, G.* (2018). Facile and highly effective synthesis of controllable lattice sulfur-doped graphene quantum dots via hydrothermal treatment of durian. *ACS Applied Materials & Interfaces*. 10(6): 5750–5759.

Wei et al., 2014 – *Wei, B., Hu, X., Li, H., Wu, C., Xu, X., Jin, Z., Tian, Y.* (2014). Effect of pHs on dispersity of maize starch nanocrystals in aqueous medium. *Food Hydrocolloids*. 36: 369-373.

Wibowo et al., 2015 – *Wibowo, D., Salamba, R., Nurdin, M., et al.* (2015). Preparation and characterization of activated carbon from coconut shell-doped TiO_2 in water solution. *Oriental Journal of Chemistry*. 31(4): 2337.

Wikipedia contributors..., 2024 – Wikipedia contributors: Agricultural waste (2024). Wikipedia, The Free Encyclopedia. 2024. [Electronic resource]. URL: https://en.wikipedia.org/wiki/Agriculturalwaste (date of access: 15.07.2024).

Yang, Park, 2019 – *Yang, G., Park, S.-J.* (2019). Conventional and microwave hydrothermal synthesis and application of functional materials: A review. *Materials*. 12(7): 1177.

Yearbook, 2013 – *Yearbook, F.S.* (2013). World food and agriculture. Food and Agriculture Organization of the United Nations, Rome 15.

Zhao et al., 2020 – *Zhao, X., Wei, C., Gai, Z., Yu, S., Ren, X.* (2020). Chemical vapor deposition and its application in surface modification of nanoparticles. *Chemical Papers*. 74: 767-778.

Zope et al., 2022 – *Zope, G., Goswami, A., Kulkarni, S.* (2022). Isolation and characterization of cellulose nanocrystals produced by acid hydrolysis from banana pseudostem. *BioNanoScience*. 12(2): 463-471.

Zuo et al., 2019 – *Zuo, K., Wu, J., Chen, S., Ji, X., Wu, W.* (2019). Superamphiphobic nanocellulose aerogels loaded with silica nanoparticles. *Cellulose*. 26(18): 9661-9671.