INTRODUCTION TO NANOMATERIALS FROM RENEWABLE RESOURCES

Abstract

Nanomaterials prepared from renewable resources have gained significant attention in recent years due to their potential to address environmental concerns and foster sustainable technological advancements. This chapter presents an overview of eco-friendly synthesis techniques, distinctive features, and wide range of applications of the developing topic of nanomaterials derived from renewable resources. The use of renewable resources such as plant extracts, agricultural waste, bio-based polymers, and algae provides a green and sustainable method of nanoparticle preparation. Green synthesis methods harness the inherent reducing and stabilizing properties of these resources, eliminating the need for hazardous chemicals and energy-intensive processes. This environmentally friendly method not only reduces environmental impact but also offers up new opportunities for the production of biocompatible and biodegradable nanomaterials. Renewable nanomaterials have flexible characteristics such as size, shape, and functionality, making them suitable for a wide range of applications. Furthermore, these nanoparticles are used in environmental remediation, providing efficient solutions for water purification, air filtration, and pollutant degradation. also the incorporation of renewable nanomaterials into traditional industries such as construction, packaging, and healthcare is gaining interest. Nanocellulose-based materials, show promise in the development of sustainable and biodegradable packaging materials, which will help to reduce plastic waste. Furthermore, incorporating them into concrete improves its mechanical properties, enabling greener and more durable building materials.

Keywords: Nanomaterials, Renewable resources, Nanocellulose

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I. INTRODUCTION

Nanotechnology, or the modification of matter at the nanoscale, has transformed several industries, providing unprecendented prospects for scientific advancement. Nanomaterials, which are defined as materials with at least one dimension in the nanoscale range (1-100 nanometers), have shown extraordinary features that distinguish them from their bulk counterparts (Nasrollahzadeh et al., 2019). While traditional nanomaterials have made great progress, there is a growing desire for sustainable alternatives to reduce the environmental impact and resource depletion associated with existing synthesis processes. This introduction delves into the developing subject of nanomaterials generated from renewable resources, which represents a promising solution to addressing these difficulties and fostering a more sustainable future (Singh, 2020).

1. **Overview of Renewable Resources And Their Significance In Nanomaterial Synthesis:** Renewable resources play a crucial role in the sustainable development of nanomaterial synthesis, contributing to environmental preservation and reducing the dependency on non-renewable sources. Nanomaterials, with their unique features and applications, have revolutionized several fields, including health, electronics, and energy storage (Kumar et al., 2010). However, their synthesis frequently involves energy-intensive and environmentally hazardous operations. Integrating renewable resources in nanomaterial synthesis not only reduces the environmental influence but also promotes the development of green and eco-friendly technology.

   First of all, naturally occurring chemicals with reducing and capping properties are a rich supply of renewable resources including plant extracts, agricultural waste, and bio-based precursors. Through green synthesis techniques, in which the stabilization of nanoparticles and the reduction of metal ions happen simultaneously, these natural agents can be employed to create nanoparticles. Green synthesis is an appealing alternative to traditional techniques because it uses less energy and no hazardous chemicals (J and Majid, 2020). A consistent manufacturing of nanomaterials is also made possible by the abundance of these resources, which guarantees a constant and sustainable supply.

   Second, renewable resources frequently contain intrinsic functional groups that can be used as templates, stabilizers, or linkers in the synthesis of nanomaterials. These functional groups aid in the management of nanoparticle size, shape, and composition, resulting in better characteristics and performance. For example, lignin derived from biomass is an effective stabilizer for metal nanoparticles and carbon compounds, conferring beneficial features such as high dispersibility and increased catalytic activity. Green functionalization approaches like this one pave the door for customizing nanomaterials to specific uses while minimizing waste and enhancing resource efficiency (Sathaye et al., 2011).

   Furthermore, renewable resources offer economic advantages. Many of these resources are readily available, inexpensive, and can be locally sourced. As a result, nanomaterial synthesis using renewable resources can lead to cost-effective production, particularly in developing regions where access to expensive precursors might be limited. Te affordability and scalability of these processes enable widespread adoption, unlocking new possibilities in areas like water purification, healthcare, and sustainable energy.

In addition to their technical significance, incorporating renewable resources in nanomaterial synthesis contributes to the broader goal of sustainable development. By utilizing these resources, the demand for non-renewable fossil fuels and petrochemical-derived precursors is reduced, thereby mitigating environmental degradation and climate change. Furthermore, green nanomaterial synthesis aligns with the principles of the circular economy, promoting a cradle-to-cradle approach where waste is minimized, and materials are reused or recycled (Alqarni et al., 2022).

Renewable resources are extremely important in nanomaterial synthesis due to their environmentally friendly character, intrinsic functional features, economic benefits, and contribution to sustainable development. We can foresee a future in which nanotechnology plays a critical role in tackling global concerns while minimising its environmental impact as academics and companies continue to explore unique ways of utilising renewable resources for nanomaterials. Using renewable resources in nanomaterial production is a critical step towards a more sustainable and environmentally friendly future.

2. **Advantages and Challenges of Utilizing Renewable Resources for Nanomaterial Production:** Utilizing renewable resources for nanomaterial production offers numerous advantages but also presents several challenges that need to be addressed for sustainable and efficient implementation.

One of the key benefits of adopting renewable resources is that they are naturally eco-friendly. Green synthesis methods, which use plant extracts, agricultural waste, or bio-based precursors, have a lower environmental impact than traditional approaches, which use toxic chemicals and energy-intensive procedures (Hussein, 2023). Nanomaterial synthesis becomes more sustainable and fits with green chemistry principles by eliminating toxic by-products and minimizing waste output.

Renewable resources are frequently easily available and can be obtained locally. This ease of access assures a consistent and continual supply of raw materials, decreasing reliance on nonrenewable resources and costly imports. The abundance of these resources makes nanomaterial manufacturing more scalable and inexpensive, especially in areas where traditional precursors are scarce.

Many renewable resources contain natural functional groups that can be used as reducing agents, stabilizers, or templates in the synthesis of nanomaterials. Because of these intrinsic qualities, nanomaterial size, shape, and composition may be precisely controlled, resulting in improved attributes and performance (Kim et al., 2021). Nanomaterials can be tailored by researchers to specific applications such as drug delivery, catalysis, and water treatment, broadening the scope of nanotechnology's influence.

The use of renewable resources in nanomaterial synthesis is consistent with broader goals of sustainable development. It reduces carbon emissions and environmental degradation by reducing demand for nonrenewable fossil fuels and petrochemical-derived precursors. Adoption of renewable resources encourages a circular economy strategy, in which waste is minimized and commodities are reused or recycled, hence increasing the environmental and economic benefits.

Renewable resource composition can vary greatly depending on factors such as geographical location, season, and growth circumstances. Natural variability may result in variable product quality and impede large-scale industrial applications. To solve these problems and ensure consistent nanomaterial performance, standardization and quality control procedures are required.

Extraction and purification of active components from renewable resources can be time-consuming and labor-intensive. To make the process economically viable, efficient extraction procedures that maximize resource utilization while minimizing waste creation are required. Furthermore, the removal of contaminants and by-products necessitates careful optimization to avoid negative effects on the final nanomaterial qualities (Chen et al., 2012). While renewable materials are often less expensive than conventional precursors, the cost-effectiveness of green synthesis processes must be carefully reviewed, especially when production is scaled up. Scaling up green synthesis processes to satisfy industrial demands may necessitate investments in advanced technologies and equipment, which may have an impact on the economic feasibility of employing renewable resources.

Despite the fact that green synthesis processes strive to reduce toxicity, some renewable resources may still contain bioactive molecules that may have unexpected consequences for human health or the environment. To assure the safety and compliance of nanomaterials created from renewable resources, rigorous testing and risk assessments are required.

Using renewable resources to produce nanomaterials has substantial advantages in terms of environmental sustainability, accessibility, customized features, and contributions to sustainable development. To fully realize the potential of renewable resources in green nanomaterial synthesis, however, issues such as batch-to-batch variability, extraction and purification processes, cost and scale-up, and safety and toxicity considerations must be addressed (Madani et al., 2022). By overcoming these obstacles, we can harness nature's strength to produce creative and sustainable nanomaterials that benefit a variety of businesses and address urgent global issues.

3. **Environmental and Sustainability Considerations in Nanomaterials From Renewable Sources:** Environmental and sustainability considerations play a crucial role in the development and utilization of nanomaterials derived from renewable sources. As the world seeks more eco-friendly and sustainable solutions, the use of renewable resources for nanomaterial production presents a promising pathway to address environmental concerns and promote a greener future (Elegbede and Lateef, 2020).

One of the primary benefits of nanomaterials from renewable sources is their reduced environmental impact. Green synthesis methods that utilize plant extracts, agricultural waste, or bio-based precursors eliminate the need for toxic chemicals and energy-intensive processes. This not only minimizes harmful by-products but also reduces carbon emissions and conserves energy, contributing to lower greenhouse gas emissions and a smaller ecological footprint (Pokrajac et al., 2021).

Another crucial consideration is resource availability and accessibility. Renewable resources, by definition, are continuously replenished, ensuring a stable and reliable supply of raw materials for nanomaterial production. This accessibility facilitates scalability and widens the reach of nanomaterial applications in various industries, making them a sustainable alternative to traditional precursors derived from finite resources.

The sustainable nature of nanomaterials from renewable sources also ties into the concept of the circular economy. By utilizing waste products or by-products from other industries, nanomaterial production can contribute to resource efficiency and waste reduction. This approach fosters a more integrated and sustainable system, where materials are reused, recycled, and reintegrated into the production process, ultimately reducing environmental impacts (Alhalili and Smiri, 2022).

However, environmental and sustainability considerations also involve challenges that must be addressed. For instance, ensuring the traceability and ethical sourcing of renewable resources is essential to prevent potential negative impacts on biodiversity and local communities. Additionally, standardized protocols for green synthesis methods need to be established to guarantee consistent and reproducible nanomaterial properties while maintaining environmental benefits. To promote the responsible and sustainable use of nanomaterials from renewable sources, life cycle assessments are crucial. Understanding the entire life cycle of these materials, from raw material extraction to disposal, enables us to identify potential environmental hotspots and make informed decisions to improve their sustainability. Moreover, a transparent and comprehensive risk assessment is necessary to evaluate the environmental and health implications of these nanomaterials throughout their life cycle.

Considering environmental and sustainability aspects in nanomaterials derived from renewable sources is vital for promoting a greener, more sustainable future. By embracing green synthesis methods and adhering to responsible sourcing and life cycle assessment practices, we can harness the potential of renewable resources to develop nanomaterials that offer innovative solutions while minimizing their environmental impact. Balancing advancements in nanotechnology with a commitment to sustainability is a necessary step towards achieving a harmonious coexistence with our planet.

II. GREEN EXTRACTION TECHNIQUES FOR RENEWABLE RESOURCES

Green extraction techniques for renewable resources have gained significant attention in recent years due to their eco-friendly nature and sustainable approach. These extraction methods aim to harness the potential of renewable resources while minimizing environmental impacts and promoting the efficient use of raw materials (Majid et al., 2023). This discussion explores the principles, advantages, and applications of green extraction techniques in the context of renewable resources.

Green extraction techniques involve using environmentally benign solvents or processes to obtain bioactive compounds, essential oils, or other valuable components from renewable resources. One of the primary principles is the replacement of hazardous or toxic solvents, such as petroleum-derived chemicals, with greener alternatives like water, ethanol, or supercritical carbon dioxide (Herrero and Ibañez, 2017). These solvents are non-toxic, biodegradable, and have a lower environmental footprint, making them ideal candidates for sustainable extraction processes.

One of the key advantages of green extraction techniques is their reduced impact on both human health and the environment. Traditional extraction methods often rely on harsh chemicals, which can pose health risks to workers and lead to environmental pollution (Cravotto et al., 2011). In contrast, green extraction methods prioritize safety and minimize the release of harmful substances into the environment, ensuring a safer workplace and healthier ecosystems.

Green extraction techniques are particularly well-suited for renewable resources, such as plant biomass and agricultural waste, which are abundant and continuously replenished. These resources offer a rich source of valuable compounds, including natural antioxidants, pharmaceuticals, and bioactive molecules. By using green extraction methods, the full potential of renewable resources can be harnessed, contributing to sustainable utilization and reducing the pressure on non-renewable resources (Koina et al., 2023). The applications of green extraction techniques in renewable resources span across various industries. In the food industry, green extraction is utilized to obtain natural food additives, flavors, and colorants from plant materials.

In the pharmaceutical sector, valuable medicinal compounds are extracted from medicinal plants using green solvents, ensuring the production of safe and sustainable medications. Additionally, green extraction methods are extensively employed in the cosmetics, nutraceutical, and biofuel industries, among others, demonstrating the versatility and broad impact of these techniques (Chemat et al., 2012). However, implementing green extraction techniques for renewable resources does present some challenges. One major obstacle is the need for optimization and standardization to achieve consistent and high yields of extracted compounds. The selection of the most suitable green solvent and extraction conditions requires careful consideration of the specific resource and desired product. Moreover, the scalability of green extraction processes to industrial levels while maintaining economic viability is an area of ongoing research(Ünlü, 2021).

The green extraction techniques for renewable resources hold tremendous potential for sustainable resource utilization and environmentally friendly extraction processes. By prioritizing safety, reducing environmental impact, and maximizing the value of renewable resources, these techniques contribute to the development of greener industries and a more sustainable future. As technology advances and more research is conducted in this field, green extraction is expected to play a pivotal role in driving the transition towards a more sustainable and eco-conscious world.

III. SUSTAINABLE EXTRACTION METHODS FOR OBTAINING NANOMATERIAL PRECURSORS FROM RENEWABLE RESOURCES

Sustainable extraction strategies for nanomaterial precursors from renewable resources have emerged as a promising option for aligning nanotechnology with environmental responsibility. These methods emphasize the extraction of important molecules from renewable sources, such as plant extracts or bio-based precursors, while minimizing environmental effect and lowering dependency on nonrenewable resources.

These sustainable extraction procedures, by utilizing green solvents and eco-friendly processes, not only provide a greener pathway for acquiring nanomaterial precursors, but also help to the development of more environmentally conscious nanotechnology practices. The incorporation of sustainable extraction methods with nanomaterial synthesis ensures a more sustainable and environmentally friendly approach, paving the path for the responsible and ethical progress of nanotechnology in a variety of industries and applications. Fig 1 shows the green extraction methods for nanoparticle preparation.

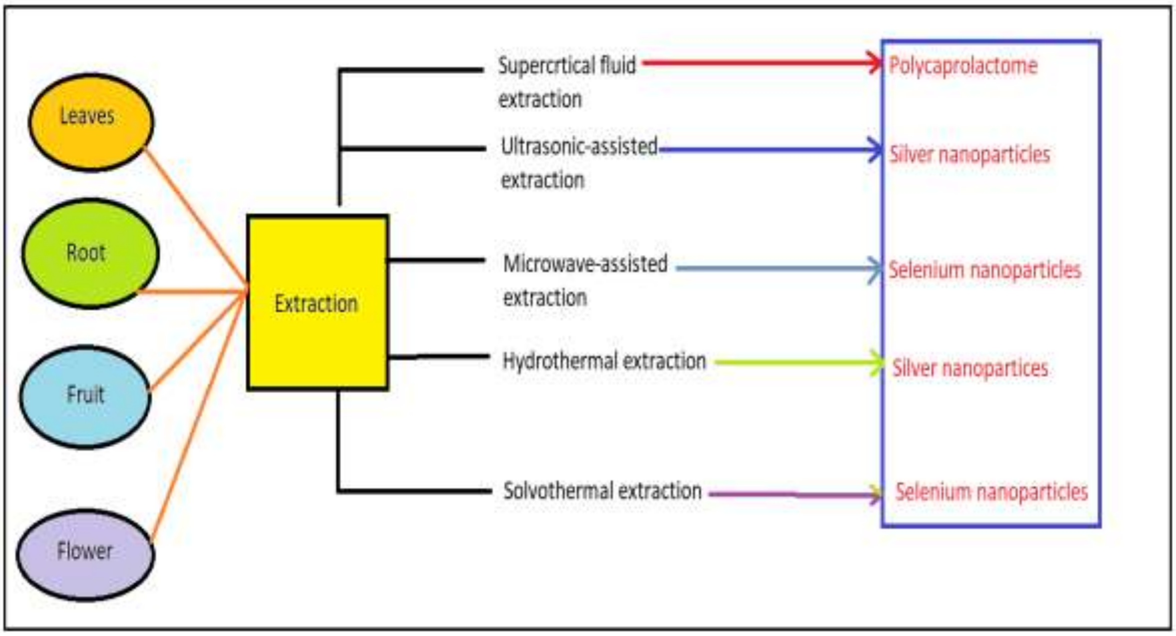

Figure 1: Green synthesis extraction of nanoparticles from renewable resources

1. **Supercritical Fluid Extraction:** Supercritical fluid extraction (SFE) has emerged as a promising technique for nanoparticle preparation due to its unique properties and advantages over conventional methods. In SFE, a supercritical fluid is employed as the solvent, typically carbon dioxide (CO_2), which is brought to its supercritical state by adjusting pressure and temperature (Kankala et al., 2017). The supercritical CO_2 exhibits excellent solvating power and mass transfer properties, allowing it to efficiently dissolve and extract the target compounds from the raw materials. Moreover, the process is easily tunable, enabling precise control over particle size and morphology by varying the extraction parameters such as pressure, temperature, and extraction time. SFE's mild operating conditions make it suitable for heat-sensitive compounds and minimize the risk of aggregation or degradation of nanoparticles (Franco and De Marco, 2021).

   One notable application of supercritical fluid extraction in nanoparticle preparation is the production of drug delivery systems. For instance, researchers have successfully utilized SFE to obtain nanoparticles loaded with therapeutic agents, such as anti-cancer drugs or antimicrobial agents. The technique enables the generation of drug-loaded nanoparticles with a high drug loading capacity, controlled release kinetics, and enhanced bioavailability, thereby improving the efficacy of the administered drugs (Akbari et al., 2020). Additionally, the environmentally friendly nature of supercritical CO_2 as a solvent makes it a desirable option for nanoparticle formulation in pharmaceutical applications

2. **Ultrasound-Assisted Extraction:** Ultrasound-assisted extraction (UAE) has emerged as a valuable and innovative technique for nanoparticle preparation. In this context, UAE is employed to extract bioactive compounds from natural sources, such as plant extracts or other biomaterials, which act as reducing agents or stabilizers in nanoparticle synthesis. The application of high-frequency ultrasound waves induces cavitation, causing the formation and implosive collapse of microbubbles (Andrade et al., 2020). This phenomenon generates localized high temperatures and pressures, enhancing mass transfer and promoting the release of bioactive compounds from the raw materials. These extracted compounds then serve as precursors for the synthesis of nanoparticles, resulting in a more sustainable and eco-friendly nanoparticle preparation process compared to traditional chemical methods.

   The use of ultrasound-assisted extraction in nanoparticle preparation offers several advantages. Firstly, the reduced extraction time and mild operating conditions minimize the risk of degradation or denaturation of bioactive compounds, leading to higher yields of the desired nanoparticles. Secondly, the controlled and tunable parameters of ultrasound, such as power intensity and exposure time, enable precise control over nanoparticle size, morphology, and dispersibility. Moreover, the absence of toxic solvents in the UAE process enhances the biocompatibility and safety of the resulting nanoparticles, making them suitable for various biomedical applications, including drug delivery, imaging, and theranostics.

- **Microwave-Assisted Extraction:** Microwave-assisted extraction (MAE) has emerged as a powerful and efficient technique for nanoparticle preparation due to its ability to enhance the extraction of bioactive compounds from various natural sources. In MAE, the application of microwave radiation generates rapid and uniform heating, leading to the disruption of plant cell walls and facilitating the release of intracellular bioactive compounds. These extracted compounds serve as the building blocks for nanoparticle synthesis, making the process more sustainable and eco-friendly compared to traditional chemical methods. Moreover, the controlled heating and reduced extraction time in MAE result in higher yields of the target compounds, leading to the production of nanoparticles with improved properties and higher purity (Sanchez Tobon et al., 2022).

  Numerous studies have investigated the application of microwave-assisted extraction for nanoparticle preparation from different raw materials. For instance, researchers have used MAE to extract bioactive compounds from plant extracts, herbal medicines, and agricultural by-products, and subsequently utilized them for the synthesis of nanoparticles with various applications in medicine, catalysis, and environmental remediation. The rapid and selective extraction capabilities of MAE make it a versatile and attractive approach for obtaining high-quality nanoparticles (Cheng et al., 2016).

3. **Hydrothermal and Solvothermal Methods:** Hydrothermal and solvothermal synthesis are two versatile methods widely employed for nanoparticle preparation, offering unique advantages in controlling size, shape, and crystallinity. In hydrothermal synthesis, the reaction is carried out under high-pressure aqueous conditions at elevated temperatures. Water acts as the solvent and also provides the necessary hydrolysis and condensation reactions for nanoparticle formation (Hayashi and Hakuta, 2010). The precise control over temperature and pressure in hydrothermal synthesis allows the synthesis of

nanoparticles with controlled size and morphology, making it suitable for a wide range of materials, including metal oxides, metal sulfides, and nanocomposites. On the other hand, solvothermal synthesis involves using organic solvents as the reaction medium, which facilitates the formation of nanoparticles at lower temperatures compared to hydrothermal conditions. This method enables the preparation of nanoparticles with high purity, well-defined crystal structures, and narrow size distributions. Solvothermal synthesis has been widely utilized for the preparation of various nanoparticles, such as metal nanoparticles, semiconductor nanocrystals, and carbon-based nanomaterials, due to its versatility and ability to achieve precise control over nanoparticle properties (Yu et al., 2016).

IV. BIOMASS-DERIVED NANOCARBONS

In recent years, the quest for sustainable and eco-friendly nanomaterials has driven significant interest in the field of biomass-derived nanocarbons. Nanocarbons are a class of nanomaterials that possess remarkable properties and find applications in various industries, including energy, environmental remediation, electronics, and biomedicine. The utilization of biomass as a renewable and abundant feedstock for nanocarbon synthesis offers a greener and more sustainable alternative to traditional carbon sources such as fossil fuels. Biomass-derived nanocarbons encompass diverse forms, including biochar, carbon nanotubes (CNTs), and graphene, each with distinct characteristics and potential applications (Yu et al., 2016).

The synthesis and application of biomass-derived nanocarbons have attracted considerable attention due to their sustainable and renewable nature, as well as their potential to revolutionize various industries. This review explores the synthesis methods, properties, and applications of biomass-derived nanocarbons, shedding light on their significance in contributing to the advancement of green nanotechnology and sustainable materials.

V. CARBON-BASED NANOMATERIALS FROM BIOMASS FEEDSTOCKS:

Carbon-based nanomaterials derived from biomass feedstocks have gained significant attention in recent years due to their sustainable and eco-friendly nature. These nanomaterials can be synthesized from various biomass sources, including agricultural residues, wood, and other organic waste materials. Three notable carbon-based nanomaterials derived from biomass feedstocks are biochar, activated carbon, and carbon nanotubes/graphene.

1. **Biochar and Its Applications In Nanotechnology:** Biochar is produced through the pyrolysis of biomass in an oxygen-limited environment, resulting in a highly porous carbon-rich material. Its unique properties, such as a large surface area and excellent adsorption capacity, make it suitable for various nanotechnological applications. Biochar-based nanocomposites have been explored for use in water purification, gas storage, and environmental remediation. In nanotechnology, biochar has shown promise as a support material for catalysts and as a precursor for the synthesis of carbon quantum dots, which are fluorescent nanoparticles with potential applications in bioimaging and sensing (Ahmad et al., 2014).

2. **Activated Carbon and Its Nanoscale Applications:** Activated carbon is another important carbon-based nanomaterial derived from biomass. Through a process of activation, biomass-derived carbon materials are exposed to high temperatures and chemical agents to create a highly porous structure with an increased surface area. These

properties make activated carbon well-suited for various nanoscale applications. Nanoscale activated carbon has been explored for use in supercapacitors, energy storage devices, and adsorbents for the removal of pollutants from air and water. Its nanoscale form allows for improved kinetics and greater efficiency in these applications (Gimba et al., 2010).

3. **Carbon Nanotubes and Graphene From Renewable Resources:** Carbon nanotubes (CNTs) and graphene are two remarkable carbon-based nanomaterials with exceptional mechanical, electrical, and thermal properties. They have been traditionally synthesized from fossil fuel-derived precursors, but recent efforts have focused on producing them from biomass feedstocks. Biomass-derived carbon nanotubes and graphene hold promise for applications in nanoelectronics, sensors, and energy storage devices (Bi et al., 2019). Additionally, the sustainable synthesis of CNTs and graphene from renewable resources aligns with the principles of green nanotechnology and contributes to reducing the environmental impact associated with their production (Zhai et al., 2022)

VI. NANOCELLULOSE: SUSTAINABLE NANOSTRUCTURED BIOMATERIALS

Nanocellulose, derived from renewable and abundant sources such as plant-based cellulose, is a sustainable and promising nanomaterial with a wide range of applications. The extraction and processing of nanocellulose involve several techniques, including mechanical, chemical, and enzymatic methods. Mechanical methods like high-pressure homogenization and microfluidization break down cellulose fibers into nanoscale dimensions, while chemical methods use acid hydrolysis or oxidation to obtain nanocellulose. Enzymatic methods, on the other hand, utilize enzymes to degrade cellulose into nanoscale particles. These extraction techniques yield nanocellulose with different morphologies, such as cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs), each exhibiting unique properties suitable for various applications (Mishra et al., 2018).

Nanocellulose finds applications in nanotechnology, electronics, and biomedicine due to its exceptional mechanical strength, high aspect ratio, and biocompatibility. In nanotechnology, nanocellulose is used as a reinforcing agent in polymer nanocomposites, enhancing the mechanical properties of the materials. Additionally, nanocellulose has been explored as a carrier for drug delivery systems, thanks to its biodegradability and non-toxic nature. In electronics, nanocellulose serves as a dielectric material in flexible and transparent electronic devices. Furthermore, nanocellulose-based nanocomposites have shown promise in water purification, catalysis, and energy storage applications (Yu, 2015).

Nanocellulose-based composites and nanocomposites are another significant area of research. By combining nanocellulose with other materials such as polymers, metals, and ceramics, the resulting composites exhibit enhanced properties and new functionalities. Nanocellulose reinforcement in polymer composites improves mechanical strength, thermal stability, and barrier properties. The incorporation of nanocellulose in cement-based materials enhances their strength and durability. Moreover, nanocellulose has been combined with conductive materials like graphene and carbon nanotubes to develop conductive nanocomposites for flexible electronics and sensors (Xie et al., 2018).

Nanocellulose is a sustainable nanostructured biomaterial with diverse applications. The extraction and processing techniques allow for the production of different forms of nanocellulose, each suitable for specific applications (Siaueira et al., 2009). Nanocellulose's unique properties make it a promising candidate in nanotechnology, electronics, biomedicine, and composite materials, paving the way for the development of environmentally friendly and high-performance materials.

VII. GREEN SYNTHESIS OF METAL AND METAL OXIDE NANOPARTICLES FROM RENEWABLE RESOURCES

Green synthesis of metal and metal oxide nanoparticles from renewable resources has emerged as an environmentally friendly and sustainable approach in nanotechnology. One of the notable methods is the biogenic synthesis of metal nanoparticles using plant extracts and microorganisms. Plant extracts, rich in bioactive compounds such as phenols, flavonoids, and terpenoids, act as reducing and stabilizing agents, facilitating the formation of metal nanoparticles (Soltys et al., 2021). Additionally, microorganisms like bacteria and fungi possess unique enzymes that can efficiently reduce metal ions to form nanoparticles. The biogenic synthesis of metal nanoparticles offers several advantages, including low-cost, non-toxicity, and scalability, making it an attractive alternative to conventional chemical methods.

Another promising avenue for green synthesis is the production of metal oxide nanoparticles from agricultural waste and natural precursors. Agricultural waste materials, such as rice husks, corn cobs, and fruit peels, contain abundant biomass and act as a valuable source of metal precursors (Singh et al., 2018). The synthesis of metal oxide nanoparticles from agricultural waste is achieved through various eco-friendly routes, including sol-gel, hydrothermal, and combustion methods.

The utilization of agricultural waste as a precursor for metal oxide nanoparticles not only reduces waste generation but also contributes to the development of sustainable nanotechnology. The applications of green-synthesized metal and metal oxide nanoparticles span across various fields due to their unique properties and environmentally friendly characteristics. In the biomedical sector, green-synthesized nanoparticles are utilized in drug delivery systems, diagnostic imaging, and antimicrobial agents (Singh et al., 2016). Their biocompatibility and controlled release properties make them suitable candidates for targeted drug delivery. Green-synthesized nanoparticles also find applications in environmental remediation, catalysis, and water purification. Their high surface area and surface reactivity enhance their adsorption and catalytic capabilities, making them effective in removing pollutants from air and water (Beyth et al., 2015).

In the field of energy, green-synthesized metal and metal oxide nanoparticles are used as efficient catalysts in fuel cells and renewable energy technologies. They improve the conversion efficiency of energy storage devices and enable the development of eco-friendly energy systems. In addition, these nanoparticles find applications in electronics and sensors, where their unique electronic and optical properties enhance the performance of devices and systems.

Green-synthesized nanoparticles have shown promise as building blocks for flexible electronics and wearable sensors due to their eco-friendly nature and excellent electrical conductivity (Srivastava et al., 2006). The green synthesis of metal and metal oxide nanoparticles from renewable resources presents a sustainable and innovative approach in nanotechnology. By harnessing the power of nature and utilizing renewable resources, researchers are paving the way for the development of nanoparticles. Table 1.1 shows the list of nanomaterials prepared by green synthesis methods.

Table 1: List of metal nanoparticles prepared by green synthesis method

S. No	Metal Nano materials	Reducing agent	Source of extract	Size of prepared nanopartice	Reference
1	Ag	Terpenoids, polyphenols, and alkaloids	Tectona grandis	10 – 30 nm	(Rautela et al., 2019)
2	Ag	flavones, ketones, amides	Combretum indicum	50 – 120 nm	(Bahuguna et al., 2016)
3	Ag/Gold	Terpenoids, alkaloids	Mentha piperita (peppermint)	5 – 150 nm	(Mittal et al., 2013)
4	Indium oxide	Terpenoids	Aloe vera (Aloe barbadensis Miller)	5 – 50 nm	(Phokha et al., 2008)
5	Cu	Hydrazine hydrate	-	80 -130 nm	(Raut et al., 2009)
6	Gold	Apiin	Apiin extracted from henna leaves	7.5 – 65 nm	(Kasthuri et al., 2009)
7	Indium oxide	-	Aloe vera (Aloe barbadensis Miller	5 - 50	(Iravani, 2011)

VIII. LIGNIN-BASED NANOMATERIALS

Lignin-based nanomaterials have gained increasing attention as sustainable alternatives in nanotechnology. Lignin, a complex aromatic biopolymer derived from plant cell walls, is one of the most abundant natural resources on Earth. The isolation and modification of lignin for nanomaterial synthesis involve several techniques, including depolymerization, fractionation, and chemical modifications (Spence et al., 2011). These processes enable the production of lignin nanoparticles with controlled size and properties, suitable for various applications. Lignin nanoparticles possess unique characteristics such as high aspect ratios, good mechanical strength, and antioxidant properties, making them valuable nanomaterials in various fields.

Lignin nanoparticles and nanocomposites have shown great promise in diverse applications. Lignin-based nanoparticles can be incorporated into polymers, ceramics, and other materials to enhance their mechanical properties and thermal stability. Lignin nanoparticles have been used as reinforcing agents in composite materials, providing higher strength and toughness.

Additionally, lignin nanocomposites can be utilized in packaging materials, construction, and automotive industries, contributing to the development of eco-friendly and sustainable materials (Lu and Hsieh, 2010). The potential applications of lignin-derived nanomaterials extend beyond nanocomposites. Lignin nanoparticles can be used as carriers for drug delivery, as they have excellent biocompatibility and can be functionalized to target specific cells or tissues. Lignin-based nanoparticles have shown promise in cancer therapy, delivering anticancer drugs to tumor sites more effectively. Furthermore, lignin nanomaterials have applications in water treatment and environmental remediation (Liu et al., 2020). Lignin-based nanocomposites have been used in wastewater treatment, removing pollutants and heavy metals effectively due to their adsorption capabilities.

The use of lignin-derived nanomaterials in energy storage devices is another exciting area of research. Lignin nanoparticles can be integrated into electrodes of batteries and supercapacitors, enhancing their electrochemical performance. The renewable nature of lignin makes it an attractive candidate for sustainable energy storage technologies (Manjarrez Nevárez et al., 2011). Lignin-based nanomaterials hold great potential in nanotechnology and beyond. The isolation and modification of lignin allow for the synthesis of lignin nanoparticles with tailored properties, making them versatile in various applications, from nanocomposites to drug delivery and environmental remediation. The abundance of lignin as a renewable resource further supports its role in developing sustainable nanotechnologies (Zhang et al., 2021).

IX. NANOPARTICLES FROM BIO-BASED POLYMERS

Nanotechnology has revolutionised many fields by offering innovative approaches at the nanoscale. Nanoparticles made from bio-based polymers have received particular attention because to their renewability, biocompatibility, and eco-friendliness. This article investigates the promise of renewable polymer-based nanoparticles, with a particular emphasis on chitosan nanoparticles and their numerous applications, as well as the use of starch and cellulose-based nanoparticles in nanomedicine and beyond (Vatanpour et al., 2016).

The first category of interest lies in renewable polymer-based nanoparticles. As the world seeks more sustainable alternatives to conventional materials, bio-based polymers emerge as promising candidates. These polymers, derived from renewable sources such as plants and microbes, offer several advantages over their synthetic counterparts. Their abundance in nature and reduced environmental impact make them an attractive choice for nanoparticle synthesis (Quiñones et al., 2018). With the increasing need for sustainable technologies, researchers have successfully synthesized nanoparticles from various bio-based polymers, contributing to the advancement of green nanotechnology.

One of the most widely explored bio-based polymers for nanoparticle development is chitosan. Chitosan, derived from the deacetylation of chitin, exhibits remarkable biocompatibility, biodegradability, and non-toxicity (Riva et al., 2011). Consequently, chitosan nanoparticles have found diverse applications in biomedicine, drug delivery, tissue engineering, and agriculture. The tunable properties of chitosan nanoparticles, such as size, charge, and functionalization, allow for targeted and controlled drug release, improving therapeutic efficacy and reducing side effects. Furthermore, chitosan nanoparticles have demonstrated great potential in gene delivery and wound healing, making them a versatile platform for various biomedical applications. Starch and cellulose, abundant in plant-based materials, represent another class of sustainable and eco-friendly applications in various industries.

Nanoparticles derived from bio-based polymers are a viable path for ecologically benign and sustainable nanotechnology applications. The use of renewable polymer-based nanoparticles, notably chitosan nanoparticles, has enabled breakthroughs in medication delivery, tissue engineering, and agriculture. Furthermore, starch and cellulose-based nanoparticles have tremendous potential in nanomedicine and other sectors, demonstrating their versatility and adaptability. The invention of these environmentally benign nanoparticles expands the scope of green nanotechnology, giving novel solutions to global concerns while minimizing environmental effect.

X. RENEWABLE BIO POLYMERS USED FOR NANOPARTICLE SYNTHESIS

Their inherent biocompatibility, low cost, and availability make them attractive candidates for applications in nanomedicine and beyond. Starch-based nanoparticles have been investigated as carriers for drug delivery systems, offering sustained release profiles and increased drug stability. In addition, cellulose-based nanoparticles have shown promise in tissue engineering, due to their biodegradability and ability to mimic the extracellular matrix. These plant-derived nanoparticles present exciting opportunities for greener nanotechnology solutions, paving the way for Renewable polymer-based nanoparticles

1. **Algal-Derived Nanomaterials:** Algae, a broad range of photosynthetic microorganisms, have emerged as a promising and long-term source of nanomaterial production. Algal species are abundant in a variety of aquatic environments, and their cultivation requires little resources and does not compete with arable land, making them a more environmentally friendly alternative to traditional nanoparticle synthesis processes. Algae can bioaccumulate metal ions and other precursors from their surroundings, making it possible to easily produce nanoparticles with low environmental impact. Moreover, algae offer the potential for large-scale cultivation, making them suitable for industrial applications in nanotechnology. The unique properties of different algal species, such as their cell wall compositions and metabolite profiles, allow for the tailored synthesis of a wide range of nanoparticles with diverse applications (Sharma et al., 2016).

   The green synthesis of nanoparticles utilizing algae extracts and biomass has gained popularity due to its favourable ecological impact, low cost, and ease of synthesis. Algal extracts, such as aqueous or alcoholic extracts, operate as reducing and stabilizing agents in the production of nanoparticles. The unique composition of these extracts imparts selectivity and control over nanoparticle size and shape, leading to tunable properties. Furthermore, using algal biomass as a precursor for nanoparticle synthesis provides a sustainable method of converting waste into valuable nanomaterials (Singh et al., 2016). Green synthesis eliminates the need for harmful chemicals and energy-intensive processes, resulting in nanoparticles with enhanced biocompatibility and reduced toxicity. The biogenic synthesis of nanoparticles using algae holds great promise for a wide range of applications, including drug delivery, catalysis, and environmental remediation.

   Algal-based nanomaterials have shown immense potential for environmental and biomedical applications due to their unique properties and eco-friendly synthesis. In environmental applications, algal-derived nanoparticles have been explored for wastewater treatment, heavy metal removal, and pollutant degradation. Their high surface area, biocompatibility, and efficient metal ion adsorption make them effective agents for environmental remediation (Wang et al., 2015).

Additionally, algal-based nanomaterials have demonstrated promise in drug delivery and imaging applications in biomedicine. The controlled release of therapeutics, enabled by the tunable properties of these nanoparticles, enhances their efficacy and minimizes side effects. Furthermore, algae-derived nanomaterials have been investigated for bioimaging and theranostics, combining diagnosis and therapy in a single platform. These multifunctional algal-based nanomaterials offer great potential for addressing critical challenges in both environmental and biomedical fields (Venkatesan et al., 2016).

2. **Future Prospects and Emerging Trends in Nanomaterials from Renewable Resources:** The future of nanomaterials from renewable resources holds great promise, driven by continuous research and innovation in this field. Researchers are exploring novel methods for the green synthesis of nanomaterials using a wide range of renewable resources such as plant extracts, agricultural waste, and bio-based polymers (Das et al., 2015). The emergence of these sustainable nanomaterials has opened up new possibilities for various applications, including electronics, energy storage, and environmental remediation. With a strong focus on eco-friendly and biocompatible materials, renewable nanomaterials are expected to play a crucial role in addressing global challenges while reducing the environmental impact of conventional nanotechnology (Huston et al., 2021)

3. **Integration of Renewable Nanomaterials into Mainstream Industries:** Sustainable growth must start with the adoption of renewable nanomaterials in established sectors. Industries are investigating the possibilities of renewable nanomaterials in sectors like packaging, building, and healthcare as the demand for environmentally friendly solutions rises. Due to their superior mechanical properties and biodegradability, nanocellulose-based materials, for example, are being investigated as sustainable substitutes for conventional packaging materials (Siqueira et al., 2010). Similarly, renewable nanomaterials are being incorporated into concrete to enhance its strength and durability while reducing the environmental footprint of construction. The integration of these materials into various industries not only improves product performance but also supports a circular economy by promoting resource efficiency and minimizing waste.

XI. ROLE OF RENEWABLE NANOTECHNOLOGY IN A SUSTAINABLE FUTURE

By addressing environmental problems and minimizing dependency on non-renewable resources, renewable nanotechnology plays a vital role in constructing a sustainable future. Nanotechnology contributes to the creation of green and eco-friendly solutions in a variety of areas by utilizing natural and renewable materials. Sustainable nanomaterials are gaining importance in fields like agriculture, where they offer targeted delivery of fertilizers and pesticides, reducing their environmental impact and optimizing resource utilization. Furthermore, in the energy sector, renewable nanomaterials show potential in improving the efficiency of solar cells and energy storage devices, promoting the shift towards clean and renewable energy sources. As these technologies mature and become more accessible, renewable nanotechnology is expected to contribute significantly to achieving global sustainability goals.

In conclusion, the future prospects of nanomaterials from renewable resources are promising and offer exciting opportunities for sustainable development. The integration of renewable nanomaterials into mainstream industries facilitates the transition towards eco-friendly and resource-efficient solutions. In a sustainable future, renewable nanotechnology will continue to play a pivotal role in addressing global challenges, promoting cleaner industries, and driving innovation in various sectors. Embracing the potential of renewable nanomaterials will be essential in building a greener and more sustainable world (Zhang et al., 2013).

XII. CONCLUSION

In conclusion, the study of nanomaterials derived from renewable resources presents a promising avenue for addressing the pressing challenges of our time, such as environmental sustainability and resource scarcity. Through the utilization of renewable materials at the nanoscale, we can unlock a plethora of innovative applications across various industries, ranging from energy and electronics to medicine and environmental remediation. The unique properties of nanomaterials offer unprecedented opportunities for enhancing the performance of existing technologies while reducing their environmental impact. Moreover, the integration of renewable resources into the production of nanomaterials can foster a circular economy, promoting a sustainable approach to material sourcing and utilization.

As research in this field continues to advance, it is essential to prioritize responsible and ethical practices to ensure the safe deployment of nanomaterials from renewable resources. Alongside scientific exploration, collaborative efforts between academia, industry, and policymakers are crucial to establish robust frameworks for evaluating the environmental and health impacts of these materials. Embracing the potential of nanomaterials from renewable resources represents a transformative step towards a more sustainable future, where cutting-edge technology aligns harmoniously with nature, propelling us towards a greener and more equitable world. By harnessing the power of nanotechnology in conjunction with renewable resources, we can pave the way for a more resilient and environmentally conscious society.

REFERENCES

[1] Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S., Ok, Y.S., 2014. Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere 99, 19–33. https://doi.org/10.1016/j.chemosphere.2013.10.071

[2] Akbari, Z., Amanlou, M., Karimi-Sabet, J., Golestani, A., Niassar, M.S., 2020. Application of supercritical fluid technology for preparation of drug loaded solid lipid nanoparticles. International Journal of Nanoscience and Nanotechnology 16, 13–33.

[3] Alhalili, Z., Smiri, M., 2022. The Influence of the Calcination Time on Synthesis of Nanomaterials with Small Size, High Crystalline Nature and Photocatalytic Activity in the TiO2 Nanoparticles Calcined at 500 °C. Crystals 12. https://doi.org/10.3390/cryst12111629

[4] Alqarni, L.S., Alghamdi, M.D., Alshahrani, A.A., Nassar, A.M., 2022. Green Nanotechnology: Recent Research on Bioresource-Based Nanoparticle Synthesis and Applications. Journal of Chemistry 2022. https://doi.org/10.1155/2022/4030999

[5] Andrade, I.H.P., Otoni, C.G., Amorim, T.S., Camilloto, G.P., Cruz, R.S., 2020. Ultrasound-assisted extraction of starch nanoparticles from breadfruit (Artocarpus altilis (Parkinson) Fosberg). Colloids and Surfaces A: Physicochemical and Engineering Aspects 586. https://doi.org/10.1016/j.colsurfa.2019.124277

[6] Bahuguna, G., Kumar, A., Mishra, N.K., Kumar, C., Bahlwal, A., Chaudhary, P., Singh, R., 2016. Green synthesis and characterization of silver nanoparticles using aqueous petal extract of the medicinal plant

Combretum indicum. Materials Research Express 3, 1–6. https://doi.org/10.1088/2053-1591/3/7/075003

[7] Beyth, N., Houri-Haddad, Y., Domb, A., Khan, W., Hazan, R., 2015. Alternative antimicrobial approach: Nano-antimicrobial materials. Evidence-based Complementary and Alternative Medicine 2015. https://doi.org/10.1155/2015/246012

[8] Bi, Z., Kong, Q., Cao, Y., Sun, G., Su, F., Wei, X., Li, X., Ahmad, A., Xie, L., Chen, C.M., 2019. Biomass-derived porous carbon materials with different dimensions for supercapacitor electrodes: A review. Journal of Materials Chemistry A 7, 16028–16045. https://doi.org/10.1039/c9ta04436a

[9] Chemat, F., Vian, M.A., Cravotto, G., 2012. Green Extraction of Natural Products : Concept and Principles 8615–8627. https://doi.org/10.3390/ijms13078615

[10] Chen, X., Li, C., Grätzel, M., Kostecki, R., Mao, S.S., 2012. Nanomaterials for renewable energy production and storage. Chemical Society Reviews 41, 7909–7937. https://doi.org/10.1039/c2cs35230c

[11] Cheng, Y.-L., Lee, C.-Y., Huang, Y.-L., Buckner, C.A., Lafrenie, R.M., Dénommée, J.A., Caswell, J.M., Want, D.A., Gan, G.G., Leong, Y.C., Bee, P.C., Chin, E., Teh, A.K.H., Picco, S., Villegas, L., Tonelli, F., Merlo, M., Rigau, J., Diaz, D., Masuelli, M., Korrapati, S., Kurra, P., Puttugunta, S., Picco, S., Villegas, L., Tonelli, F., Merlo, M., Rigau, J., Diaz, D., Masuelli, M., Tascilar, M., de Jong, F.A., Verweij, J., Mathijssen, R.H.J., 2016. We are IntechOpen , the world ' s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %. Intech 11, 13.

[12] Cravotto, G., Binello, A., Orio, L., Group, B., 2011. Green extraction techniques.

[13] Das, S., Sen, B., Debnath, N., 2015. Recent trends in nanomaterials applications in environmental monitoring and remediation. Environmental Science and Pollution Research 22, 18333–18344. https://doi.org/10.1007/s11356-015-5491-6

[14] Elegbede, J.A., Lateef, A., 2020. Nanotechnology in the built environment for sustainable development. IOP Conference Series: Materials Science and Engineering 805. https://doi.org/10.1088/1757-899X/805/1/012044

[15] Franco, P., De Marco, I., 2021. Nanoparticles and nanocrystals by supercritical CO2-assisted techniques for pharmaceutical applications: A review. Applied Sciences (Switzerland) 11, 1–27. https://doi.org/10.3390/app11041476

[16] Gimba, C.E., Salihu, A.A., Kagbu, J.A., Itodo, M.T.A.U., Sariyya, A.I., 2010. Study of Pesticide (Dichlorvos) Removal from Aqueous Medium By Arachis Hypogaea (Groundnut) Shell Using GC / MS. World Rural Observations 2, 1–9.

[17] Hayashi, H., Hakuta, Y., 2010. Hydrothermal Synthesis of metal oxide nanoparticles in supercritical water. Materials 3, 3794–3817. https://doi.org/10.3390/ma3073794

[18] Herrero, M., Ibañez, E., 2017. SC. The Journal of Supercritical Fluids. https://doi.org/10.1016/j.supflu.2017.12.002

[19] Hussein, H.S., 2023. The state of the art of nanomaterials and its applications in energy saving. Bulletin of the National Research Centre 47. https://doi.org/10.1186/s42269-023-00984-4

[20] Huston, M., Debella, M., Dibella, M., Gupta, A., 2021. Green synthesis of nanomaterials. Nanomaterials 11, 1–29. https://doi.org/10.3390/nano11082130

[21] Iravani, S., 2011. Green synthesis of metal nanoparticles using plants. Green Chemistry 13, 2638–2650. https://doi.org/10.1039/c1gc15386b

[22] J, C.R.K., Majid, M.A., 2020. Renewable energy for sustainable development in India: current status, future prospects, challenges, employment, and investment opportunities. Energy, Sustainability and Society, 10(1) | 10.1186/s13705-019-0232-1. Energy, Sustainability and Society 10, 1–36.

[23] Kankala, R.K., Zhang, Y.S., Wang, S. Bin, Lee, C.H., Chen, A.Z., 2017. Supercritical Fluid Technology: An Emphasis on Drug Delivery and Related Biomedical Applications. Advanced Healthcare Materials 6. https://doi.org/10.1002/adhm.201700433

[24] Kasthuri, J., Veerapandian, S., Rajendiran, N., 2009. Biological synthesis of silver and gold nanoparticles using apiin as reducing agent. Colloids and Surfaces B: Biointerfaces 68, 55–60. https://doi.org/10.1016/j.colsurfb.2008.09.021

[25] Kim, Y.J., Hong, H., Yun, J.H., Kim, S. Il, Jung, H.Y., Ryu, W.H., 2021. Photosynthetic Nanomaterial Hybrids for Bioelectricity and Renewable Energy Systems. Advanced Materials 33, 1–21. https://doi.org/10.1002/adma.202005919

[26] Koina, I.M., Sarigiannis, Y., Hapeshi, E., 2023. Green Extraction Techniques for the Determination of Active Ingredients in Tea : Current State , Challenges , and Future Perspectives.

[27] Kumar, A., Kumar, K., Kaushik, N., Sharma, S., Mishra, S., 2010. Renewable energy in India: Current status and future potentials. Renewable and Sustainable Energy Reviews 14, 2434–2442. https://doi.org/10.1016/j.rser.2010.04.003

[28] Liu, R., Dai, L., Xu, C., Wang, K., Zheng, C., Si, C., 2020. Lignin-Based Micro- and Nanomaterials and

their Composites in Biomedical Applications. ChemSusChem 13, 4266–4283. https://doi.org/10.1002/cssc.202000783

[29] Lu, P., Hsieh, Y. Lo, 2010. Preparation and properties of cellulose nanocrystals: Rods, spheres, and network. Carbohydrate Polymers 82, 329–336. https://doi.org/10.1016/j.carbpol.2010.04.073

[30] Madani, M., Hosny, S., Alshangiti, D.M., Nady, N., Alkhursani, S.A., Alkhaldi, H., Al-Gahtany, S.A., Ghobashy, M.M., Gaber, G.A., 2022. Green synthesis of nanoparticles for varied applications: Green renewable resources and energy-efficient synthetic routes. Nanotechnology Reviews 11, 731–759. https://doi.org/10.1515/ntrev-2022-0034

[31] Majid, I., Khan, S., Aladel, A., Dar, A.H., Adnan, M., 2023. Recent insights into green extraction techniques as efficient methods for the extraction of bioactive components and essential oils from foods. CyTA - Journal of Food 21, 101–114. https://doi.org/10.1080/19476337.2022.2157492

[32] Manjarrez Nevárez, L., Ballinas Casarrubias, L., Canto, O.S., Celzard, A., Fierro, V., Ibarra Gómez, R., González Sánchez, G., 2011. Biopolymers-based nanocomposites: Membranes from propionated lignin and cellulose for water purification. Carbohydrate Polymers 86, 732–741. https://doi.org/10.1016/j.carbpol.2011.05.014

[33] Mishra, R.K., Ha, S.K., Verma, K., Tiwari, S.K., 2018. Recent progress in selected bio-nanomaterials and their engineering applications: An overview. Journal of Science: Advanced Materials and Devices 3, 263–288. https://doi.org/10.1016/j.jsamd.2018.05.003

[34] Mittal, A.K., Chisti, Y., Banerjee, U.C., 2013. Synthesis of metallic nanoparticles using plant extracts. Biotechnology Advances 31, 346–356. https://doi.org/10.1016/j.biotechadv.2013.01.003

[35] Nasrollahzadeh, M., Sajadi, S.M., Sajjadi, M., Issaabadi, Z., 2019. An Introduction to Nanotechnology, 1st ed, Interface Science and Technology. Elsevier Ltd. https://doi.org/10.1016/B978-0-12-813586-0.00001-8

[36] Phokha, Sumalin, Seraphin, Supapan, Maensiri, S., Laokul, P., Klinkaewnarong, J., Phokha, S, Seraphin, S, 2008. Indium oxide (In2O3) nanoparticles using Aloe vera plant extract: Synthesis and optical properties Indium oxide (In 2 O 3) nanoparticles using Aloe vera plant extract: Synthesis and optical properties. Optoelectronics and Advanced Materials-Rapid Communications 2, 161–165.

[37] Pokrajac, L., Abbas, A., Chrzanowski, W., Dias, G.M., Eggleton, B.J., Maguire, S., Maine, E., Malloy, T., Nathwani, J., Nazar, L., Sips, A., Sone, J., Van Den Berg, A., Weiss, P.S., Mitra, S., 2021. Nanotechnology for a Sustainable Future: Addressing Global Challenges with the International Network4Sustainable Nanotechnology. ACS Nano 15, 18608–18623. https://doi.org/10.1021/acsnano.1c10919

[38] Quiñones, J.P., Peniche, H., Peniche, C., 2018. Chitosan based self-assembled nanoparticles in drug delivery. Polymers 10, 1–32. https://doi.org/10.3390/polym10030235

[39] Raut, D., Wankhede, K., Vaidya, V., Bhilare, S., Darwatkar, N., Deorukhkar, A., Trivedi, G., Salunkhe, M., 2009. Copper nanoparticles in ionic liquids: Recyclable and efficient catalytic system for 1,3-dipolar cycloaddition reaction. Catalysis Communications 10, 1240–1243. https://doi.org/10.1016/j.catcom.2009.01.027

[40] Rautela, A., Rani, J., Debnath (Das), M., 2019. Green synthesis of silver nanoparticles from Tectona grandis seeds extract: characterization and mechanism of antimicrobial action on different microorganisms. Journal of Analytical Science and Technology 10. https://doi.org/10.1186/s40543-018-0163-z

[41] Riva, R., Ragelle, H., Des Rieux, A., Duhem, N., Jérôme, C., Préat, V., 2011. Chitosan and chitosan derivatives in drug delivery and tissue engineering. Advances in Polymer Science 244, 19–44. https://doi.org/10.1007/12_2011_137

[42] Sanchez Tobon, C., Ljubas, D., Mandić, V., Panžić, I., Matijašić, G., Ćurković, L., 2022. Microwave-Assisted Synthesis of N/TiO2 Nanoparticles for Photocatalysis under Different Irradiation Spectra. Nanomaterials 12. https://doi.org/10.3390/nano12091473

[43] Sathaye, J., Lucon, O., Rahman, A., Christensen, J., Denton, F., Fujino, J., Heath, G., Mirza, M., Rudnick, H., Schlaepfer, A., Shmakin, A., 2011. Chapter 9 - Renewable Energy in the Context of Sustainable Development, IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. https://doi.org/10.1017/CBO9781139151153.013

[44] Sharma, A., Sharma, S., Sharma, K., Chetri, S.P.K., Vashishtha, A., Singh, P., Kumar, R., Rathi, B., Agrawal, V., 2016. Algae as crucial organisms in advancing nanotechnology: a systematic review. Journal of Applied Phycology 28, 1759–1774. https://doi.org/10.1007/s10811-015-0715-1

[45] Siaueira, G., Bras, J., Dufresne, A., 2009. Cellulose whiskers versus microfibrils: Influence of the nature of the nanoparticle and its surface functionalization on the thermal and mechanical properties of nanocomposites. Biomacromolecules 10, 425–432. https://doi.org/10.1021/bm801193d

[46] Singh, J., Dutta, T., Kim, K.H., Rawat, M., Samddar, P., Kumar, P., 2018. “Green” synthesis of metals and

their oxide nanoparticles: Applications for environmental remediation. Journal of Nanobiotechnology 16, 1–24. https://doi.org/10.1186/s12951-018-0408-4

[47] Singh, P., Singh, H., Kim, Y.J., Mathiyalagan, R., Wang, C., Yang, D.C., 2016. Extracellular synthesis of silver and gold nanoparticles by Sporosarcina koreensis DC4 and their biological applications. Enzyme and Microbial Technology 86, 75–83. https://doi.org/10.1016/j.enzmictec.2016.02.005

[48] Singh, T., 2020. 1 . Nanotechnology System Introduction to Nanotechnology System Origin of Nanotechnology. https://doi.org/10.13140/RG.2.2.12770.15049/1

[49] Siqueira, G., Bras, J., Dufresne, A., 2010. Cellulosic Bionanocomposites: A Review of Preparation, Properties and Applications 728–765. https://doi.org/10.3390/polym2040728

[50] Soltys, L., Olkhovyy, O., Tatarchuk, T., Naushad, M., 2021. Green synthesis of metal and metal oxide nanoparticles: Principles of green chemistry and raw materials. Magnetochemistry 7. https://doi.org/10.3390/magnetochemistry7110145

[51] Spence, K.L., Venditti, R.A., Rojas, O.J., Habibi, Y., Pawlak, J.J., 2011. A comparative study of energy consumption and physical properties of microfibrillated cellulose produced by different processing methods. Cellulose 18, 1097–1111. https://doi.org/10.1007/s10570-011-9533-z

[52] Srivastava, V.C., Mall, I.D., Mishra, I.M., 2006. Characterization of mesoporous rice husk ash (RHA) and adsorption kinetics of metal ions from aqueous solution onto RHA. Journal of Hazardous Materials 134, 257–267. https://doi.org/10.1016/j.jhazmat.2005.11.052

[53] Ünlü, A.E., 2021. Green and Non ‑ conventional Extraction of Bioactive Compounds from Olive Leaves : Screening of Novel Natural Deep Eutectic Solvents and Investigation of Process Parameters. Waste and Biomass Valorization 12, 5329–5346. https://doi.org/10.1007/s12649-021-01411-3

[54] Vatanpour, V., Yekavalangi, M.E., Safarpour, M., 2016. Preparation and characterization of nanocomposite PVDF ultrafiltration membrane embedded with nanoporous SAPO-34 to improve permeability and antifouling performance. Separation and Purification Technology 163, 300–309. https://doi.org/10.1016/j.seppur.2016.03.011

[55] Venkatesan, J., Kim, S.K., Shim, M.S., 2016. Antimicrobial, antioxidant, and anticancer activities of biosynthesized silver nanoparticles using marine algae ecklonia cava. Nanomaterials 6. https://doi.org/10.3390/nano6120235

[56] Wang, Aiqin, Li, P., Dai, Y., Zhang, J., Wang, Ai-qin, Wei, Q., 2015. Chitosan-Alginate Nanoparticles as a Novel Drug Delivery System for Nifedipine Chitosan-Alginate Nanoparticles as a Novel Drug Delivery System for Nifedipine 4, 221–228.

[57] Xie, H., Du, H., Yang, X., Si, C., 2018. Recent Strategies in Preparation of Cellulose Nanocrystals and Cellulose Nanofibrils Derived from Raw Cellulose Materials. International Journal of Polymer Science 2018. https://doi.org/10.1155/2018/7923068

[58] Yu, H., 2015. Hydroxypropyl Cellulose-Based Graft Copolymers: Structure, Properties, and Application. Cellulose-Based Graft Copolymers 446–475. https://doi.org/10.1201/b18390-23

[59] Yu, X., Marks, T.J., Facchetti, A., 2016. Metal oxides for optoelectronic applications. Nature Materials 15, 383–396. https://doi.org/10.1038/nmat4599

[60] Zhai, Z., Zhang, L., Du, T., Ren, B., Xu, Y., Wang, S., Miao, J., Liu, Z., 2022. A review of carbon materials for supercapacitors. Materials and Design 221, 111017. https://doi.org/10.1016/j.matdes.2022.111017

[61] Zhang, Q., Uchaker, E., Candelaria, S.L., Cao, G., 2013. Nanomaterials for energy conversion and storage. Chemical Society Reviews 42, 3127–3171. https://doi.org/10.1039/c3cs00009e

[62] Zhang, Z., Terrasson, V., Guénin, E., 2021. Lignin nanoparticles and their nanocomposites. Nanomaterials 11. https://doi.org/10.3390/nano11051336