Advances in Manufacturing of Carbon-based Molecular Nanomaterials Based on Rice Husk/hull Waste

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This review highlights potential application areas for carbon-based molecular nanoparticles, such as carbon dots, carbon nanotubes, graphene quantum dots, and carbon quantum dots. The success of nano-manufacturing hinges on robust collaboration between academia and industry to advance applicable manufacturing techniques. Choosing the right approach is crucial, one that integrates the carbon base of nanomaterials with the required properties and impurities, as well as the scalability of the process. Molecular, in this context, refers to the nanoscale carbon structures that form the basis of these materials, including their arrangement, bonding, and properties at the molecular level. The article also explores the characterization of different types of molecular nanomaterials. Nanomaterials are increasingly used in almost every contemporary industry, including construction, textiles, manufacturing, and computing. This article reviews the most prominent sectors globally that employ nanomaterials. Biomasses containing lignin, cellulose, and hemicellulose have become some of the most extensively studied. Initially, rice waste was utilized for bulk materials, but lately, the production of multifunctional materials has surged in interest. Carbon nanostructures derived from rice waste offer a broad spectrum of applications and enhanced biocompatibility. Recent advancements, challenges, and trends in the development of multifunctional carbon-based nanomaterials from renewable rice waste resources are considered.

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INTRODUCTION

Molecular carbon-based nanomaterials, derived from rice husk, are noted for their unique properties and wide range of applications. These materials include graphene, carbon nanotubes, and fullerenes, which are distinguished by their molecular structures that contribute to their exceptional optical, electrical, mechanical, and thermal properties. The integration of these molecular nanomaterials into various industries, such as construction, textiles, manufacturing, and computing, showcases their versatility and the potential for significant advancements in technology and sustainability (Hu *et al.* 2010; Mubarik *et al.*

2021; Wang *et al.* 2018a). The rapid pace of urbanisation and industrialization over the previous few decades has resulted in serious environmental problems (Ouyang *et al.* 2020). Abbas *et al.* (2018) has described the energy scarcity, limited access, and excessive use of resources, which together pose significant challenges. Researchers Hu and colleagues developed practical solutions in response to the challenges brought by global changes in temperature and contamination in environment (Hu *et al.* 2010; Palanisamy *et al.* 2023; 2024). Sustainable energy sources include agricultural leftovers and forest by-products. Biomass production is estimated to be between 150 and 200 billion metric tonnes per year (Raja *et al.* 2019). In the cutting-edge world of nanotechnology (Wang *et al.* 2020), the topic of using a 'waste to riches' strategy has discussed by Wang *et al.* (2018c), and Boruah *et al.* (2020). The conversion of biomass waste into extremely valuable commodities has enormous economic and environmental benefits, and it has gotten a lot of attention in recent years. The objective of this article is to provide a comprehensive review of the recent advancements, challenges, and trends in the development and application of carbon-based molecular nanomaterials derived from rice husk and hull waste. It examines the processes involved in the synthesis and characterization of these nanomaterials, discusses the economic and environmental benefits of converting rice waste into high-value multifunctional materials, and identifies the challenges and future prospects in the field of carbon nanomaterials derived from renewable biomass sources. By achieving these objectives, the article seeks to provide a valuable resource for researchers and industry professionals interested in the sustainable and innovative use of agricultural waste for advanced material applications (Singh *et al.* 2017).

Various agricultural byproducts including rice husk, banana fibers, sugarcane fibers, and palm kernel shells have been explored for applications such as water treatment, energy storage, and medical uses. Recently, there has been significant interest in carbon-based materials derived from green synthesis waste products. Rice husk, which is rich in cellulose and lignin, serves as a valuable source for carbon nanomaterials. These carbon nanomaterials, produced from agricultural waste, exhibit exceptional optical, electrical, mechanical, and thermal properties, making them useful in numerous fields (Mubarik *et al.* 2021; Mylsamy *et al.* 2024; Palaniappan *et al.* 2024; Sumesh *et al. 2024*). Due to the rising demand for carbon nanomaterials (CNMs), researchers are increasingly focusing on obtaining CNMs from biomass. This approach ensures that the derived CNMs possess the desired characteristics, leveraging the abundant and renewable nature of biomass sources. By using biomass, researchers aim to produce high-quality CNMs that exhibit excellent optical, electrical, mechanical, and thermal properties, making them suitable for a wide range of applications, including water treatment, energy storage, and medical uses (Wang *et al.* 2018b). The ability to transform low-value natural waste resources into valuable goods is remarkable. This innovative approach not only adds economic value to otherwise discarded materials but also promotes sustainability by reducing waste, utilizing renewable resources (Deng *et al.* 2016; Mohammadinejad *et al.* 2016), and it has piqued the interest of analysts for the past 20 years (Tamirat 2017).

Carbon nanomaterials (CNMs) derived from agricultural waste are a type of engineered nanomaterials (ENMs) that are known for their broad spectrum of exceptional properties. These CNMs exhibit remarkable optical, electrical, mechanical, and thermal characteristics, making them highly versatile and valuable in various applications. The use of agricultural waste to produce CNMs not only adds economic value to low-value resources, but it also promotes environmental sustainability by reducing waste and utilizing renewable materials (Change 2005). It is estimated that 7.8 billion tonnes of industrial waste are generated annually (Asif and Hasan 2018). Paddy rice comprises 75% starchy endosperm, 15% rice husk, and 10% bran layers. Upon burning, 10 to 15% of the rice husk transforms into rice husk ash (RHA). Rice husk, which is rich in hemicellulose, cellulose, and lignin, is a sustainable and carbon-rich material. It is extensively utilized as a raw material to produce high-value carbon materials, including graphene, fullerenes, carbon nano-fullerenes, and carbon nanotubes (CNTs) (Mubarik *et al.* 2021).

Rice husk (RH), a byproduct of rice production, can be transformed into silica (SiO_2) and carbon-based nanomaterials, offering environmental and economic benefits. RH accounts for 20% of rice waste by weight and contains 70 to 80% organic matter. Its composition mainly includes lignin, cellulose, SiO_2, and alkalis and depends on plant variety, climatic conditions, and geographic location (Ali *et al.* 2021). Burning RH produces rice husk ash, about 25% of the original weight, leading to environmental pollution and disposal issues. While RH is abundant, it can negatively impact the environment, human health, and animal health if not managed properly (Castro-Ladino *et al.* 2023; Santulli *et al.* 2023). Nevertheless, it has interest due to its chemical components (Teo *et al.* 2016). Rice husk (RH) is a valuable alternative precursor for producing graphite oxide materials, which are crucial in various applications including green nanocomposites, supercapacitors, conductive materials, adsorbents, biomedical nanomaterials, batteries, electronic devices, heating devices, solar cells, and sensors. These carbon nanomaterials, including carbon dots, carbon nanotubes, graphene quantum dots, and carbon quantum dots, produced from agricultural waste, exhibit exceptional optical, electrical, mechanical, and thermal properties, making them useful in numerous fields. These carbon-based materials have demonstrated significant potential across a broad range of applications due to their unique properties (Mubarik *et al.* 2021).

BACKGROUND ABOUT RICE HUSK

Muñoz-Écija *et al.* (2019) conducted research on rice husk, which has been one of the most prominent and frequently studied forms of biomass in recent decades. This interest is partly due to the output of over 156 million tonnes of rice husk annually (Kolahalam *et al.* 2019). As nanoscience and nanotechnology have advanced, rice husks have been utilized to develop extensive carbon- and silicon-based nanostructures. The unique design and material organization of rice husk biomass have led to the creation of various innovative nanostructures. Rice husk-derived nanostructures (RH-NSs) have recently garnered significant attention due to their effectiveness in various applications, including cells, batteries, nano-generators, and electrodes. Chakroborty and co-authors explored converting rice husk, abundant in India, into carbon-based nanomaterials, utilizing its rich cellulose, lignin, and silica content. This process not only promotes sustainable agricultural practices but it also offers environmental and industrial benefits, highlighting innovative recycling methods that transform agricultural waste into valuable resources (Chakroborty *et al.* 2023; Ramasubbu *et al.* 2024). Yuan *et al.* (2024) transformed rice husk (RH) into silica nanoparticles *via* calcination and sol–gel processes, assessing their composition, structure, and size. Such work highlights the sol–gel and freeze-drying methods' efficacy in producing uniform, spherical nanoparticles, emphasizing the sustainable conversion of agricultural waste into industrial precursors (Yuan *et al.* 2024). Azam *et al.* (2018) review the synthesis of carbon nanomaterials (CNMs) from palm oil waste, examining methods like chemical vapor deposition and pyrolysis. The study outlines synthesis conditions, applications, and future directions, offering a guide for creating carbon-based nanostructures from palm oil waste for various applications (Azam *et al.* 2018; Kurien *et al.* 2023). A green method was developed using silica nanoparticles from rice husk ash to remove toxic heavy metals from potatoes in contaminated soils (Nizamani *et al.* 2024; Valdés *et al.* 2014). This cost-effective approach leverages agricultural waste to ensure food safety, showcasing high adsorption capabilities and minimal processing, marking a significant stride towards mitigating health risks associated with metal pollution.

RICE HUSK DERIVED CARBON-BASED MOLECULAR NANOMATERIALS

Carbon is the most adaptable element in the periodic table because it has a large number of different types and strengths of bonds that it may form with a variety of other elements, as well as graphene, carbon nanotubes, and fullerenes, which are all low-dimensional allotropes of carbon generated by alloy procedures. Representation of several carbon allotropes, including fullerene and graphene, is presented in Fig. 1. Nanomaterials of various types have been discovered, but carbon-based nanomaterials are particularly important in nanotechnology (Hu *et al.* 2010). The four main kinds of carbon nanostructures are graphite (three dimensions), graphene (two dimensions), carbon nanotubes (one dimension), and fullerenes (zero dimension). Table 1 below details the dimensions of nanoparticles.

Table 1. Dimensionality in Nanoparticles

Dimensions	Ranges	Example
Zero-D	No dimension - nanoscale	Nano-porous material
One-D	1- dimension - nanoscale	Graphene Sheet
Two-D	2- dimension - nanoscale	Nanowires
Three-D	3- dimension - nanoscale	Dendrimers

Carbon Dots

Carbon Dots (CDs) are a novel class of carbon nanomaterials that have attracted significant attention due to their unique optical properties, low toxicity, and high biocompatibility. CDs typically possess sizes below 10 nm and exhibit excellent photoluminescence, which makes them suitable for applications in bioimaging, drug delivery, and sensing. The synthesis of CDs from biomass sources such as rice husk involves processes like hydrothermal treatment and microwave-assisted methods. The resulting CDs have been found to have high quantum yield and stability, making them promising candidates for various biomedical and environmental applications (Mubarik *et al.* 2021).

Carbon Nanotubes

Carbon Nanotubes (CNTs) are cylindrical nanostructures composed of rolled-up sheets of single-layer carbon atoms (graphene). They exhibit remarkable electrical, thermal, and mechanical properties, which make them suitable for a wide range of applications, including in electronics, nanocomposites, and energy storage devices. CNTs can be synthesized from rice husk through chemical vapor deposition (CVD) and other methods. The use of rice husk as a precursor not only provides a cost-effective and sustainable source of carbon, but it also helps in reducing agricultural waste. CNTs derived from rice husk have shown excellent performance in applications such as supercapacitors and sensors (Fathy 2017).

Graphene Quantum Dots

Graphene Quantum Dots (GQDs) are small fragments of graphene with sizes less than 20 nm. They exhibit unique properties such as tunable photoluminescence, high surface area, and excellent biocompatibility. GQDs are synthesized through methods including chemical exfoliation and hydrothermal cutting of larger graphene sheets. Rice husk-derived GQDs have been explored for their potential in bioimaging, photovoltaic devices, and light-emitting diodes (LEDs). The production of GQDs from rice husk not only utilizes waste biomass but also offers a green and sustainable approach to nanomaterial synthesis (Singh *et al.* 2017).

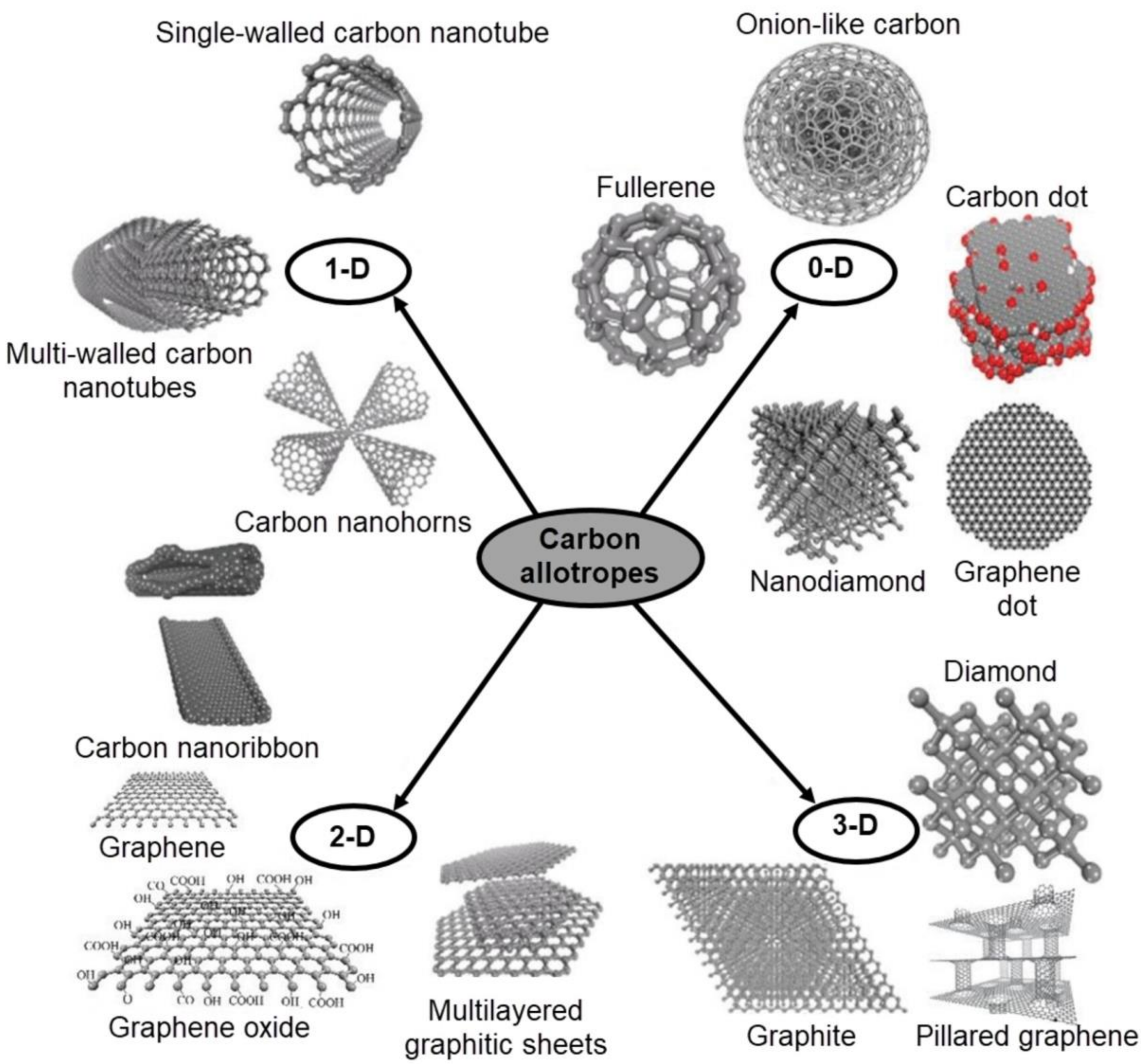


Fig. 1. Fullerene and graphene are range of different carbon allotropes (Georgakilas *et al.* 2015; Mubarik *et al.* 2021)

Carbon Quantum Dots

Carbon Quantum Dots (CQDs) are a subset of carbon dots that are typically smaller and exhibit quantum confinement and edge effects, resulting in distinct electronic and optical properties. CQDs are known for their high quantum yield, photostability, and low toxicity, making them ideal for applications in bioimaging, drug delivery, and environmental monitoring. The synthesis of CQDs from rice husk involves techniques such as pyrolysis and solvothermal methods. CQDs derived from rice husk have demonstrated excellent fluorescence properties and are being explored for use in sensors, photocatalysis, and energy conversion devices (Asnawi *et al.* 2018).

Nanomaterials have many uses and are widely synthesised because of their interesting chemical and physical characteristics, such as their large surface area, unusual morphological shapes, and high quantum yield. Graphite, diamond, and carbon nanotubes (both single-walled and multi-walled carbon nanotubes) are all instances of such materials. Different carbon-based nanomaterials' diameters are shown in Fig. 2. The versatility of these materials makes them attractive in the field of biomedicine. In addition, preexisting biomaterials may have their functioning improved by adding carbon-based nanoparticles. Consequently, carbon-based nanostructures are finding use in a wide range of biomedical fields, including as bio-imaging, delivery of drugs, treatment of wastewater, catalyst support, pollution in the air management, conversion of energy, cellular sensors, hydrogen preservation, and energy storage, *etc*. Among their many other applications, they may be found in automobiles, cosmetics, aeroplanes, sporting goods, materials for soft turbine blades, and water turbines. Ecological warmth, cost-effectiveness, and unique features, such as an extensive surface area for the functionalization with diverse functional groups and minerals, make biomass-derived carbon nanotubes extremely intriguing (Wang *et al.* 2020). Some characteristics of these nanomaterials are shown in Table 2.

Table 2. Characteristics of Various Carbon-based Molecular Nanomaterials (Asnawi *et al.* 2018; Mubarik *et al.* 2021)

Carbon Material	Dimensions	Hardness	Tenacity	Electrical Conductivity (S/m)
Graphite	3D	High	Flexible, non-elastic	3.3×10^3
Graphene	2D	Highest	Flexible, elastic	$10^5 – 10^6$
Carbon Nanotube	1D	High	Elastic	$10^5 – 10^7$
Fullerene	0D	High	Elastic	10^{-5}
Carbon Dots	0D	Medium	Flexible, elastic	$10^{-3} – 10^{-1}$
Carbon Quantum Dots	0D	Medium	Flexible, elastic	$10^{-2} – 10^{-1}$
Graphene Quantum Dots	0D	Medium	Flexible, elastic	1 – 10
Activated Carbon	3D	Medium	Brittle	$10^{-6} – 10^{-4}$
Nanodiamonds	0D	Very High	Hard, non-elastic	$1– 10^2$

Graphene is a type of nanocarbon that is used in many areas, including electronics, solar cells, biological sensors, and more. The many environmental and agricultural uses of carbon-based nanomaterials are shown in Fig. 3.

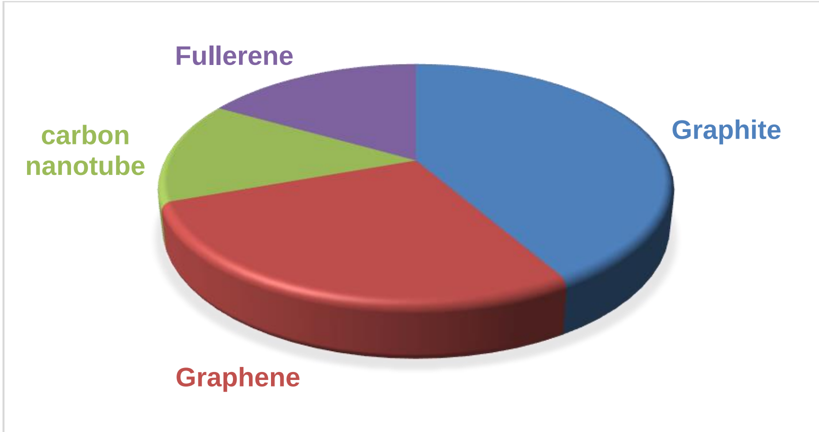


Fig. 2. Diverse carbon-based molecular materials

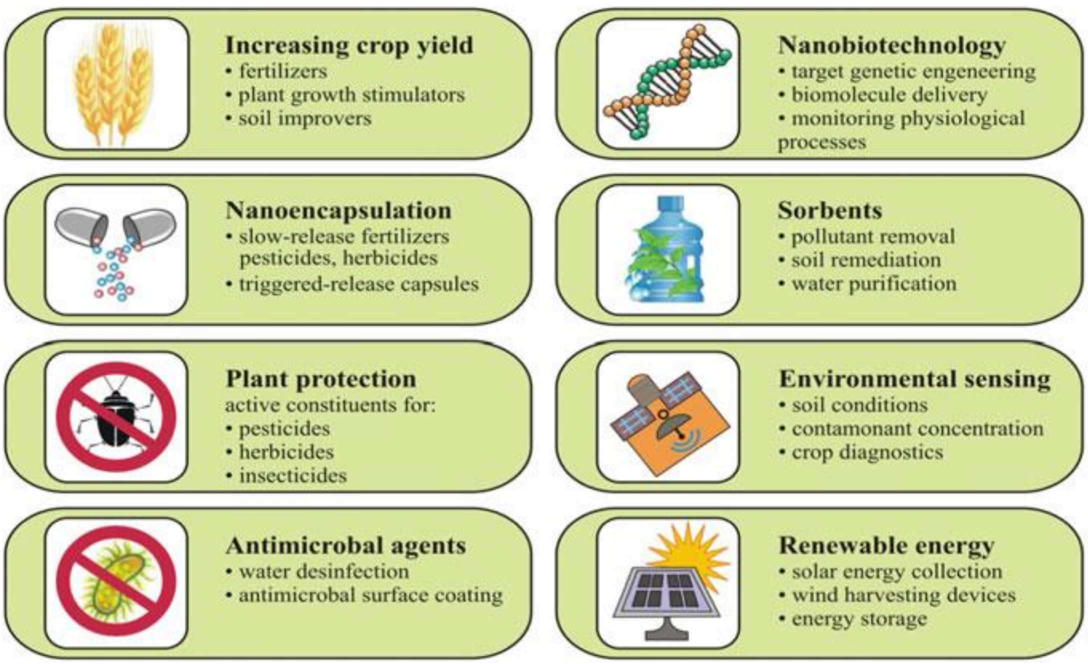


Fig. 3. Summarized nanoscaled carbon material applications in environmental and farming areas (Abdien *et al.* 2016; Georgakilas *et al.* 2015; Zaytseva and Neumann 2016).

FABRICATION AND CHARACTERIZATION OF CARBON-BASED MOLECULAR NANOMATERIALS UTILIZING RICE WASTE

Nanoparticles can be assembled utilising a variety of techniques, including biological, physical, and chemical approaches. For example, extracellularly generated gold nanoparticles of 11 to 19 nm size can be made utilizing photosynthetic bacteria such as *Rhodopseudomonas* capsulate in this scenario (Singh and Kundu 2014). Extracellular silver nanoparticles can also be made utilising the *Fusarium oxysporum* fungus. Furthermore, employing *Sargassum wightii* algae, roughly 88 percent of gold nanoparticles were produced within 12 hours of incubation. Silver nanoparticles can be made utilising biomolecules found in the peel of an orange (*Citrus clementina*) (Ashique *et al.* 2022).

Fabrication and characterization biological, physical, and chemical approaches are all used to make nanoparticles. Pyrolysis, which involves heating a precursor in the substantial absence of oxygen, is the most common method for producing large-scale NPs in industry. Thermal deposition is another top-down approach, in which the chemical bonds of the precursors are broken by an endothermic chemical breakdown induced by heating. The chemical approach is critical for the creation of molecular nanomaterials in the gas and liquid phases. Co-precipitation is a chemical process for making nanoparticles that requires combining two or more divalent and trivalent metal ions in water. The aqueous solutions are continually agitated, and heat and reducing agents may or may not be required (Horikoshi *et al.* 2010). Another chemical method is the sono-chemical method, which involves ultrasonication in a liquid media to create NPs.

The process begins with (i) using ferrocene-nickel catalysts or ferrocene to create hydrothermally treated CNT bundles that are reinforced with rice stubble, and then (ii) depositing camphor onto these bundles using chemical vapour deposition. The shape of CNTs was studied using transmission electron microscopy (TEM) and scanning electron microscopy (SEM), while thermal stability (TGA) and electronic characteristics (Raman spectroscopy) were judged independently (Itkis *et al.* 2005).

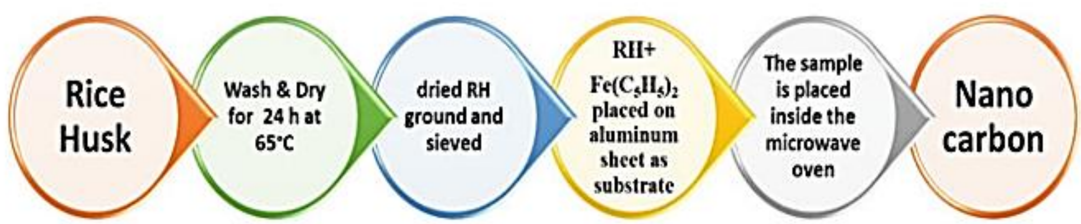


Fig. 4. Synthesis of nanocarbon from rice husk

Carbon nanotubes (CNTs) and other carbon nanostructures were created by Asnawi *et al.* (2018) using RH, as seen in scheme 6. The catalytic synthesis of CNTs after many RH washing and drying steps is the basis of this fast and inexpensive process. Chemical vapour deposition was used by Fathy *et al.* (2017) to carbonise treated RHs, resulting in the creation of CNTs. Two processes, hydrothermal treatment and chemical vapour deposition, were used to synthesize CNTs. Fathy (2017) investigated this technology for (i) producing CNT bundles that have been hydrothermally treated using ferrocene-nickel catalysts or ferrocene and (ii) chemical vapour deposition of camphor onto ferrocene-nickel catalysts or ferrocene. The shape of carbon nanotubes was studied using transmission electron microscopy and scanning electron microscopy, while thermal degradation analysis and Raman spectroscopy were used to evaluate their electrical characteristics and thermal stability, respectively (Fathy 2017).

A green strategy to mitigate nanotoxicity involves a combination method wherein organic extracts serve as reducing agents. Recently, advanced microwave devices have been developed to control temperature and other reaction parameters in both laboratory and industrial settings (Huguet-Casquero *et al.* 2021). However, because microwave heating is dependent on a molecule's dipole moment, results are often highly dependent on the content of moisture. A thin film is a layer of material that ranges in thickness from a few nanometers (monolayer) to a few micrometres (multilayer) in nanofabrication. Systems that involve changing one of the four states of matter can be achieved using suction systems. The tiny layer is then moulded to perfection. This is a bottom-up approach. To achieve acceptable film consistency, this type of sputtering requires an objective material that is larger than the substrate. DLS (Dynamic Light Scattering), XRD (X-Ray Diffraction), SEM (Scanning Electron Microscope), TEM (Transmission Electron Microscope), LLS (Laser Light Scattering), AES (Auger Electron Spectroscopy), XPS (X-ray Photoelectron Spectroscopy), and other technologies are commonly used to characterise molecular nanomaterials. Particle shape and size are usually the most important data gathered at the start of NP characterisation (Bushell *et al.* 2020).

Physical activation, chemical activation, and hydrothermal carbonization are some of the methods used to produce carbon nanomaterials from biomass (Muñoz-Écija *et al.* 2019; Uniyal *et al.* 2024). Rice husk is a readily available natural resource for producing potential carbon nanomaterials. Activated carbon (AC) is commonly utilized as an adsorbent in traditional wastewater treatment. The application of nanoscale carbon materials, such as carbon nanotubes (CNTs), shows promising potential for enhancing wastewater remediation, as evidenced by numerous studies. Micro-pollutants, including cysteines (cyanobacterial toxins), lead, and copper ions, can be adsorbed on the surface of CNTs. Moreover, multi-walled carbon nanotubes (MWCNTs) have been employed to adsorb antibiotics, herbicides, and nutrients like nitrogen and phosphorus from wastewater. The primary advantages of nanocarbons include a large surface area, exceptional mechanical and thermal stability, affinity for aromatic compounds, and potent antibacterial properties. CNTs have also been modified with antimicrobial agents to serve as disinfectants and combat antimicrobial resistance. Silver-coated CNTs, as hybrid nanoparticles, have been utilized as antimicrobial agents (Arora and Attri 2020).

GRAPHENE

Graphene, a material composed of sp2-hybridized carbon atoms arranged in a two-dimensional (2D) hexagonal lattice, was first isolated in 2004 using a technique called micromechanical cleavage. Known for its remarkable physical, chemical, optical, electronic, and mechanical properties, graphene has gained significant attention across various fields. It is highly suitable for a wide range of applications, including electronics, composites, sensors, and energy storage devices due to its excellent conductivity, strength, flexibility, and transparency (Ghuge *et al.* 2017). Rice husk (RH) can be utilized as a carbon source, with potassium hydroxide (KOH) serving as an activating agent in the production of graphene. Biomass such as RH is a cost-effective, abundant, and environmentally friendly alternative for producing carbon materials, such as graphene oxide fibers (GOF). Graphene's properties, including hydrophobicity, have sustained its research interest.

Although these materials are costly and less available, their potential remains high. Singh *et al.* (2017) successfully created graphene layers using rice husk ash (RHA) and KOH, proving that rice by-products are viable graphene sources, thus boosting the economic and environmental value of agricultural waste (Singh *et al.* 2017).

Table 3. Bibliography of Research on Carbon-based Molecular Nanostructures Derived from Biomass (Zhao *et al.* 2019)

Raw Materials	Mixture Method	Reaction Condition	Final Product
Rice husk	Chemical activation	450-850 °C	Few layered graphene
Rice straw	Chemical activation	650 °C	Graphene
Rice husk	Chemical activation	800 °C	Multi-layered graphene oxide
Rice husk	Microwave- assisted	600-700 °C	Graphene
Rice bran	Microwave- assisted	250 °C	Graphene oxide
Rice straw	Microwave- assisted	0 °C	Graphene oxide

Such unusual properties of graphene have opened the door to a lot of interesting physics and suggested that graphene may be used in a variety of advanced electronics. While Fig. 5 depicts an idealized, perfect structure of graphene, it is important to note that most graphene products described in recent literature exhibit a much more complex structure with partial oxidation. This complexity arises during the synthesis process and affects the material's properties, including its electrical conductivity and mechanical strength. Understanding these imperfections is crucial for practical applications, as they influence the performance and suitability of graphene in various advanced technologies.

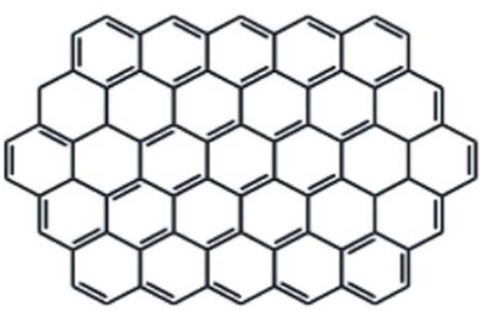


Fig. 5. Single-layer graphene

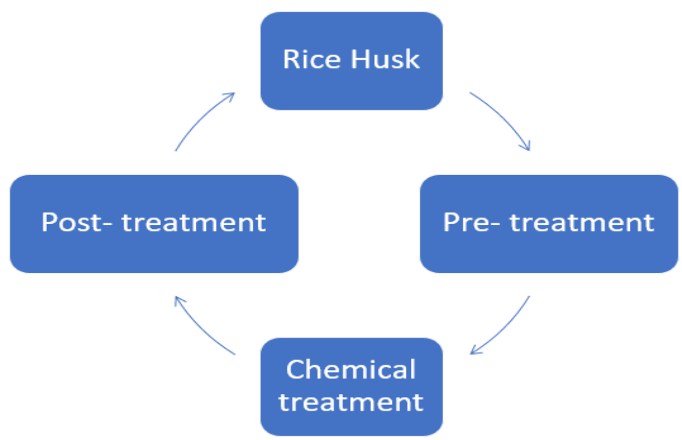
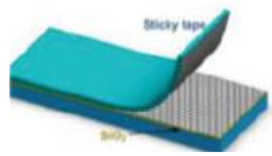
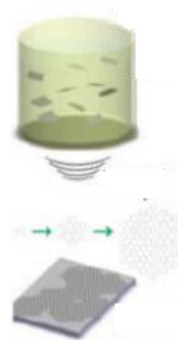
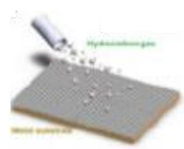
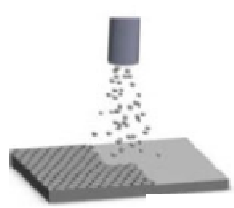


Fig. 6. Graphene produced from rice husk is combined in this flow chart

The synthesis of graphene is categorized into two principal styles: (a) top-down and (b) bottom-up approaches (refer to Table 4).

Table 4. Various Approaches for the Synthesis of Graphene (Ismail *et al.* 2019)

Type	Method	Figure/illustration	Advantages	Disadvantages
Top-down approach (from graphite)	Mechanical exfoliation	 Micromechanical cleavage	Fewer defects	Neither scalable nor capable for mass production
	Chemical method		Cost-effective and suitable for mass production	Utilize many toxic chemicals throughout the synthetic process
Bottom-up approach (from carbon)	Chemical vapor deposition (CVD)		Compatible with the current complementary metal-oxide semii conductor (CMOS) large technology due to large area and high-quality graphene produced	Expensive and incloves complex transfer process
	Epitaxial growth	Molecular beam  Substrate	No defects for every single graphene	Discontinous

Crashworthiness tests, including axial, transverse, and radial compressions, were conducted at the LMP Research and Development Lab in Erode. The tests employed a servo-hydraulic computerized universal testing machine (Kalpak – KIC-2-1000C, Serial Number 121101; Kalpak Instruments and Controls Pvt, Ltd., India) with interchangeable load cells and a 25 kN capacity. This setup from LMP Research and Development Lab ensured accurate evaluations of the tubes' structural performance under different loading conditions (Prasath *et al.* 2020; Govindarajan *et al.* 2024, 2024a).

TOXICITY AND ADSORPTION ABILITY OF CARBON-BASED MOLECULAR NANOMATERIALS

NC materials, characterized by their large surface area, surface functionalization, and porous structure, show promise as sorbents for the removal of organic and inorganic toxins (Mahfoudhi and Boufi 2017). When bulk materials are reduced to the nanoscale, a large number of formerly harmless compounds become poisonous. Nanomaterials can be found in a variety of places in everyday life, including combustion engines in automobiles. If carbon nanotubes and fullerene are breathed into the lungs, they can be extremely hazardous. Because toxicological testing is time-consuming and expensive, analysts are developing computational models to predict how nanomaterials will behave in biological systems. Nanomaterials-based products are gradually infiltrating people's daily lives. Engineered nanoparticles, as well as the myriad goods and components that make them up, are not subject to any specific regulations. There is currently no recognised and uniform regulation for the use of nanomaterials, nor is there a single worldwide agency to oversee it (Naidu 2020).

Carbon nanoparticles' large surface area, high efficiency in cellular absorption, and ability to deliver drugs to specific tumours have made them very attractive as drug nanocarriers in the biomedical field. Due to these characteristics, nanoparticles may carry chemotherapeutic medicines straight to cancer spots, where they may have less of an impact (Garriga *et al.* 2020). A number of obstacles, however, must be overcome before clinical use becomes a realistic possibility. The main worry is the possibility of carbon nanoparticles becoming harmful in the long run. To advance the development of sophisticated, multifunctional carbon nanomaterials for cancer therapy, comparative in vitro cytotoxicity studies from various synthesis sources are necessary, along with assessments of drug loading efficiency and risk-benefit analysis (Garriga *et al.* 2020)

RICE HUSK AS NANOMATERIALS

While the primary focus of this article is on molecular carbon nanoparticles derived from rice husk, it is also worthwhile to explore a simpler approach that involves reducing rice husk into various types of nanoparticles, which may extend beyond the category of 'molecular carbon'. The growing importance of environmental sustainability, the scientific community has shifted its attention to developing green industrial techniques. Rice husk, a residual material from the process of milling rice, is a difficulty in terms of its large volume and its capacity to decompose naturally (Ali *et al.* 2021; Mubarik *et al.* 2021). Nevertheless, due to its composition consisting of roughly 20% silica, as well as substantial quantities of cellulose and lignin, it serves as an exceptional precursor for the production of carbon-based nanomaterials. By employing cutting-edge processing methods, it is possible to convert RH into many types of carbon, such as activated carbon, carbon nanotubes, and graphene-like structures. Each of these forms possesses distinct properties and can be utilized for specific applications. Rice husk-derived carbon nanostructures have notable potential in the field of energy storage. Carbon nanotubes and graphene sheets possess desirable characteristics such as a large surface area and excellent electrical conductivity, making them well-suited for applications in batteries and supercapacitors (Shen 2017).

Carbon nanoparticles improve electron mobility and electrochemical stability in energy storage devices, resulting in increased energy densities and faster charging rates compared to traditional materials. Activated carbon derived from RH has demonstrated significant potential in the field of environmental remediation, particularly in its ability to absorb contaminants from both water and air. The porous structure and surface chemistry of this material allow for efficient trapping of heavy metals, organic molecules, and other pollutants, making it an essential element in filtering systems. Moreover, the silica obtained from RH can be employed in the manufacturing of mesoporous silica nanoparticles, which are used in drug delivery systems because of their biocompatibility and ability to release drugs in a regulated manner (Modak *et al.* 2020). Rice husk-derived carbon nanoparticles are also utilized in the construction industry to improve the characteristics of cement and concrete. Carbon nanotubes can greatly enhance the compressive strength, durability, and resistance to environmental degradation of these materials. This not only prolongs the durability of infrastructure but also diminishes the environmental impact linked to construction activities.

Although RH-derived nanomaterials show potential for various applications, there are still several obstacles that need to be addressed (Ali *et al.* 2021). Further research and development are necessary to investigate the scalability of production processes, cost-effectiveness, and the consistency of nanomaterial qualities, as these elements are crucial. Furthermore, it is crucial to conduct a comprehensive evaluation of the environmental consequences associated with the disposal and lifetime of nanomaterials in order to guarantee the long-term viability of this strategy. This strategy adheres to the principles of circular economy and green chemistry by transforming an agricultural by-product into a useful resource. Continuing research in this sector has the potential to profoundly transform various industries, including energy storage, environmental remediation, healthcare, and building (Wang *et al.* 2018a). This may lead to a future that is both more sustainable and technologically sophisticated.

Future Research Challenges and Prospects

The lack of data, the possibility of unfavourable climate effects, human well-being, security, and maintainability are all issues of concern. Moving beyond the bench is hampered by a lack of funding for applied research, financial backer apprehension when handling new developments. Furthermore, there is concern regarding the nanoparticles' potential for injury. This reinforces the need for continued focus on the development and application of molecular carbon nanoparticles, ensuring that their potential benefits can be fully realized while addressing safety and scalability concerns. Nanotechnology's use in current water treatment has the potential to change a huge number of these cycles by lowering treatment costs and enabling the treatment of hitherto untreatable pollutants. Nanotechnology could be the source of all automotive subsystems. It includes things like using advanced nanoparticles as a tyre filler and so on. Then speculations could be made to put current hypothetical structures through rigorous testing. When faced with a slow progression, contestants shift their focus on efficiency. Normalization, specialisation, and centralization are common robotic traits that support effectiveness. Finally, for the safe use of new, massive nanomaterials technologies over the world, international nanomaterials regulation is critical.

CONCLUDING STATEMENTS

In recent years, molecular carbon nanoparticles derived from rice husk have emerged as a promising solution to several pressing global challenges, including the energy crisis, environmental pollution, and advanced biomedical applications. The unique properties of these nanoparticles, such as high surface area, electrical conductivity, and biocompatibility, make them highly versatile and effective in various applications. In industries, carbon-based molecular nanoparticles offer a wide range of applications. Nanoparticles are used in industry to improve the product that is supplied to customers. The use of nanoparticles in the food industry improves food quality by giving it a better scent and flavour. Nanoparticles are used in agriculture to make lands fruitful, as pesticides, and to reduce toxicity. Nanomaterials can be used in the textile industry to create unique textiles with a variety of purposes. Nanoparticles can help the cosmetics sector lower the toxicity of their products. Nanomaterials have been used by the pharmaceutical and medical industries to develop novel medications and better treatment alternatives for prospective patient benefit and health-care. Nanotechnology has enabled a wide range of applications, thus becoming a major concern for science and innovation strategy development. It is now used in a variety of modern areas. In conclusion, molecular nanoparticles are revolutionising industries such as the environment, manufacturing, and the computer industry, among others. Finally, an internationally recognised, stringent nano safety regulation is critical for long-term development of developing nanomaterial-based industrial uses and consumer benefits.

In environmental remediation, molecular carbon nanoparticles have been explored for their ability to adsorb pollutants and catalyze the degradation of contaminants. The looming global energy crisis and climate change have put human culture's survival and evolution in jeopardy; as a result, demand for breakthrough technologies that deliver high-performance and superior-property materials has skyrocketed. Current development in molecular carbon nanoparticles obtained from biomass has shown significant potential in addressing these issues. These nanoparticles exhibit exceptional optical, electrical, and thermal properties, making them suitable for various advanced applications, including energy storage, environmental remediation, and biomedical uses. One of the primary areas of interest is the use of molecular carbon nanoparticles in energy storage systems. Current development nanomaterials obtained from rice biomass has been discussed in this review: their favorable characteristics and promising use in numerous disciplines. Consequently, these materials have received extra care to ensure that they answer the aforementioned questions and provide a real challenge to human intervention. By conclusion, molecular carbon nanoparticles derived from rice husk hold tremendous promise for revolutionizing multiple industries while promoting environmental sustainability. Continued research and development in this area will pave the way for innovative solutions to some of the world's most critical challenges, driving progress towards a more sustainable and technologically advanced future.

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Data Availability Statement

Data is available on request from the authors.

Declaration of Conflicting Interests

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