**Nanomaterials and Their Applications in Electronics, Healthcare, and Energy**

**Jyoti Bhattacharjee, Subhasis Roy\***

Department of Chemical Engineering, University of Calcutta, 92 A. P. C. Road, Kolkata-700009, India

\* Email: subhasis1093@gmail.com/srchemengg@caluniv.ac.in

**Abstract**

The nanoscale world has emerged as a transformational field with far-reaching consequences in fields as diverse as electronics, energy, and healthcare. To address growing environmental concerns, the emphasis has been on generating eco-friendly green nanoparticles in recent years. This abstract comprehensively reviews green nanomaterials integrated with IoT (Internet of Things) and their novel contributions to sustainable technology alternatives. Green nanomaterials addressed here are used for the development of flexible and nano-biodegradable electronic components, allowing for the creation of environmentally conscious and energy-efficient electronic gadgets such as lithium-ion batteries and supercapacitors, which will improve smart grid management, energy storage capacity, and charge-discharge rates. This chapter highlights the organic nanostructures coupled with IoT in advancing renewable energy technologies in the energy sector. Nanoparticles such as quantum dots, fullerenes, smart dust, and perovskite nanocrystals discussed here, have enormous potential in solar cell applications, capturing and converting solar energy effectively. This chapter focuses on the green nanomaterial revolution in diagnostics, drug delivery, and therapies. Nanorobots from biocompatible sources, such as chitosan and silk fibroin, have been discussed to increase drug delivery, reduce side effects, and enhance therapy results. Ethical concerns about using nanotubes in consumer items and medicine are also addressed to ensure responsible innovation. Wearable IoT-integrated electro spun nanofibers have continuously been examined to track body temperature, pulse, and breathing rate. Challenges and current developments in biosensors, IoT, and material science are portrayed in this chapter.

**Keywords**

Green nanostructures, IoT, nanoelectronics, smart devices, wearable sensors, self-powered.

**1. Introduction:**

“Nanotechnology is a science, a method, and a machine for manufacturing the future.” -Edilson Gomes de Lima. The term "machine" implies using nanotechnology as a transformative force, propelling developments and innovations across different industries. Nanotechnology has the potential to revolutionize industrial processes, leading to the development of cutting-edge technologies and products that will have a huge impact on the future. Green nanoscience is the fabrication and application of nanostructures and a fundamental understanding of the relationships between physical attributes and material dimensions. Green nanomaterials have various advantages over conventional nanomaterials, including lower toxicity, biodegradability, and using renewable resources in their fabrication [1]. This chapter delves into green chemistry concepts used to synthesize these compounds, which focus on minimizing waste formation, utilizing non-toxic solvents, and employing energy-efficient procedures. As a result, green nanomaterials are essential for fostering sustainable development and lowering the total environmental effect of nanotechnology-based applications [2]. With the advent of the Internet of Things (IoT), which connects numerous devices and items to the Internet, combining green nanomaterials with IoT technology offers new possibilities and applications in electronics, energy, and healthcare. This convergence has the potential to transform many fields by improving performance, efficiency, and sustainability. Green nanomaterials, such as cellulose nanocrystals and chitosan, have been investigated for incorporation into flexible electronic devices such as flexible screens, wearable sensors, and electronic fabrics. Compared to typical electronics materials, these nanocomposites have superior mechanical qualities, low cost, and biodegradability [3]. Nanogenerators based on green nanomaterials, such as piezoelectric nanoparticles generated from bio-waste, have been studied for energy harvesting programs. The journal Bio-waste Derived Piezoelectric Nanogenerators for Sustainable Energy Harvesting, discusses nanogenerators and their ability to convert mechanical energy from the environment, such as body movements or vibrations, into electricity, which can then be used to power low-energy IoT devices. Green nano-catalysts, such as graphene-supported metal nanoparticles generated from biomass, have been investigated for various catalytic processes in energy production. They can, for instance, be utilized in fuel cells or to aid in synthesizing clean hydrogen from renewable sources [4]. As mentioned here, green nanotubes have been used to construct nanosensors capable of detecting specific biomolecules or infections in healthcare settings. These nano-sensors can be integrated into IoT devices for real-time health monitoring, illness diagnoses, and healthcare facility environmental monitoring, taken in reference from the journal Green Nano-sensors for Healthcare Monitoring. Conductive films are created using nanofibers manufactured from conductive materials such as silver nanowires or graphene. These films are used in flexible displays, touchscreens, and solar cells, and they outperform classic materials like indium tin oxide (ITO) in terms of performance and flexibility [5]. The nanofibers highlighted here, comprised of transition metal oxides or conducting polymers, can be used as high-performance battery electrodes. They have quick charge/discharge rates and increased capacity, making them useful for energy storage applications in portable devices and electric hydrogen-powered vehicles. Piezoelectric nanofibers can turn mechanical vibrations or movements into electrical energy. They can be woven into fabrics and connected to wearable devices, allowing them to be powered by body motion or environmental vibrations [6]. The comparison between the number of publications and citations vs. years on the evolution of green nanomaterials is shown in Figure 1.



**Figure 1:** Number of publications and citations on green nanomaterials from 2017 to 2022. (Data input from ScienceDirect.com).

**2. Molecular and Nanoelectronics:**

Molecular electronics is the design of single molecules to control electron transport, helping a wide variety of molecular functions for electronic gadgets. Technologies provide considerable promise for enhancing electronics capabilities and providing new functionalities. A few applications of molecular and nanoelectronics are given below:

2.1 Single-Molecule Transistors: These represent the ultimate limit of miniaturization, with individual molecules acting as transistors, the basic building blocks of modern electronic circuits. Researchers used scanning tunneling microscopy (STM) and molecular self-assembly to manufacture single-molecule transistors effectively. Carbon nanotube transistors are cylindrical carbon structures with distinct electrical characteristics. They can be utilized to make nanoscale field-effect transistors (FETs). Carbon nanotube transistors have exceptional electronic performance and can be used in various applications, including flexible electronics and biosensors [7].

2.2 Molecule Sensors: Nanoelectronics enables the construction of very sensitive sensors based on molecule or nanoscale interactions. These sensors can accurately detect a wide range of substances, including gases, chemicals, and biomolecules [8].

2.3 Molecular Quantum Computers: The concept of quantum computing at the molecular level is an intriguing field of research. Researchers are investigating using individual molecules as qubits to construct scalable and powerful quantum computing systems.

2.4 2D Materials and Beyond Two-dimensional materials, such as graphene and transition metal dichalcogenides, offer extraordinary electrical characteristics. Researchers are investigating their potential for developing revolutionary electronic gadgets with greater performance and efficiency. The gate in the nanowire-based vertical surround gate FET wraps around the nanowire channel. This distinct architecture allows for greater gate control and aids in reducing short-channel effects, which become more prominent in standard planar FETs as dimensions decrease [9]. The nanowire-based construction is especially favorable for future technological nodes in nanoelectronics since it can be scaled down more easily than standard planar FETs. This design offers a promising avenue for future miniaturization as transistors drop in size. These unique electrostatics and gate control of transistors make them ideal for high-performance applications in molecular electronics, quantum computing, and other upcoming nanoelectronic technologies.

2.5 Electronic devices that are flexible and lightweight are made using organic electronics, which use carbon-based materials (organic semiconductors). Future technologies include flexible displays that can be incorporated into surfaces or clothes and the development of organic photovoltaics for effective solar energy conversion [10].

2.6 Nanoelectronics for Brain-Computer Interfaces (BCIs): Recent developments in nanoelectronics have made it possible to create brain-computer interfaces that can establish direct contact between the brain and external gadgets. New types of human-computer interaction could be developed, which could have ground-breaking applications in restoring sensory functioning for people with disabilities.

2.7 Nanomaterials, such as nanostructured electrodes, have the potential to improve energy storage technologies. This is known as nanoelectronics in energy storage. For instance, the performance of lithium-ion batteries might be enhanced by nanoelectronics, which might also make it possible to create solid-state batteries of the future.

2.8 Quantum dots are tiny semiconductor particles with distinctive electrical characteristics. Their potential for use in optoelectronics and quantum computing has been studied. The ability of quantum dots to emit certain light hues has improved quantum dot-based displays and sensors. Quantum Dots: Applications in Biology, Journal of Physics, describes how molecular and nanoelectronics have been driving futuristic trends in biomaterials [11].

2.9 Self-Powered Nanogenerators: Self-Powered Nanogenerators (SPNGs) can capture environmental energy and transform it into electricity to power small electronic systems. They can make electricity from mechanical vibrations, friction, or temperature gradients via various methods, including piezoelectric, triboelectric, and thermoelectric effects. The use of molecular electronics for medical applications such as targeted medication delivery, bioimaging, and disease diagnostics has been investigated by researchers in nanotechnology. To enable precise and individualized medical treatments, biological systems can be coupled with nanoscale electronic devices [12]. As technology progresses, these microelectronic devices may find uses in various disciplines ranging from healthcare and environmental monitoring to computing and communication.

**3. Nanomedicine for Healthcare:**

Green nanomaterials are nanoscale that are ecologically benign, sustainable, and frequently manufactured utilizing environmentally favorable processes. These materials, when integrated with the Internet of Things (IoT), have the potential to transform the field of nanomedicine by improving drug delivery, diagnostics, and personalized medicine. The following are some applications of green nanomaterials with IoT in nanomedicine:

3.1 Green nanomaterials such as biodegradable polymers, lipid-based nanoparticles, and graphene oxide can be designed to transport medications and target specific tissues or cells in the body. These drug carriers can be remotely controlled and monitored using IoT technology, assuring exact drug delivery at the proper time and location. A smart nanodevice, for instance, may release chemotherapy medications only when cancer biomarkers are detected, limiting off-target effects and boosting treatment outcomes [13]. Green-synthesized fine particles can be functionalized with specialized targeting and imaging agents, such as gold or iron oxide nanoparticles. These nanoparticles can then be employed for tumor imaging, allowing for more precise visualization of malignancies.

3.2 Remote Patient Monitoring: IoT-enabled wearable devices and implantable nano-sensors may continually collect crucial health data such as heart rate, blood pressure, and oxygen levels. Green nanomaterials are crucial in developing biocompatible, non-toxic nano-sensors for these applications. This real-time patient monitoring improves patient care and enables the early discovery of health conditions, lowering complications and hospital visits [14].

3.3 Tissue Engineering with Artificial Intelligence: Scaffolds for tissue engineering applications can be made from green nanomaterials such as cellulose nanofibers or chitosan. When these scaffolds are combined with IoT-enabled sensors, real-time monitoring of tissue growth, integration, and healing progress is possible. This method holds promise in regenerative medicine and organ-on-a-chip technology [15].

3.4 Cancer: Green nanomaterials can produce highly sensitive and selective nano-sensors capable of detecting cancer-specific biomarkers at an early stage. The IoT connectivity enables continuous monitoring of patient biomarker levels, allowing for timely action. For example, green nanomaterials such as graphene oxide or carbon nanotubes could be employed in fabricating these sensors. A comprehensive review by Khan et al (2020) on the Green Synthesis of Silver Nanoparticles Using Plant Extracts for Cancer Therapy- examines alternative green synthesis strategies for producing silver nanoparticles from plant extracts. These nanoparticles have shown promise in cancer therapy, with cytotoxic effects on cancer cells while being biocompatible with healthy cells. Green synthesis is an environmentally friendly method that reduces the need for harmful chemicals [16].

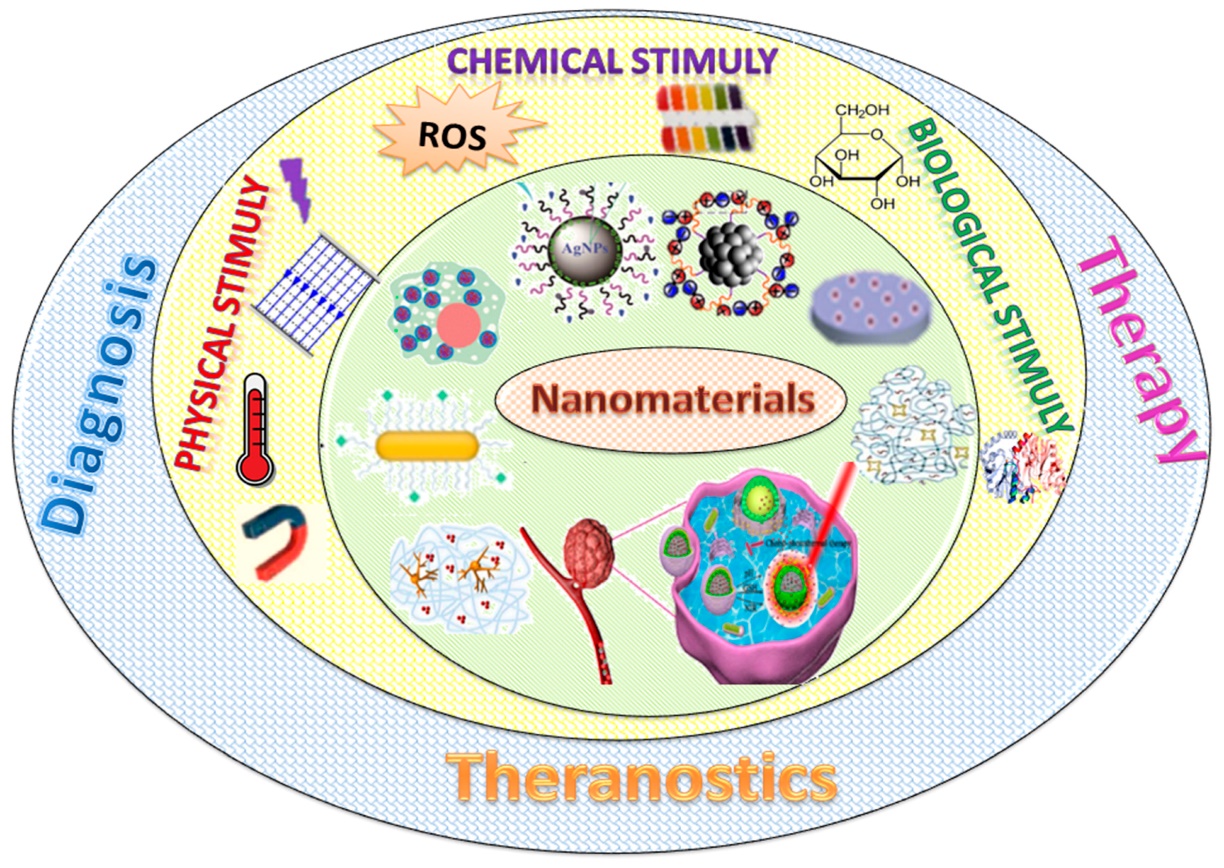
3.5 Photothermal Therapy (PTT): Several plant extracts have discovered photoactive characteristics. Nanoparticles having photothermal characteristics can be generated utilizing green synthesis approaches. These nano-shells can aggregate specifically in tumors and generate localized heat when exposed to near-infrared light, resulting in the death of cancer cells via photothermal treatment. Green nanomaterials with strong light-absorbing capabilities can be used in PTT, which uses near-infrared light to selectively heat and destroy cancer cells. IoT might monitor tumor temperature in real-time during treatment, ensuring appropriate heating without injuring healthy tissue. Green nanomaterials such as gold nanoparticles or nanocomposites are examples [17]. When subjected to an alternating magnetic field, green nanoparticles with magnetic characteristics can induce hyperthermia in cancer cells. To maximize the therapeutic impact, IoT can precisely control magnetic field strength and dispersion. One possible contender for such uses is green iron oxide nanoparticles.

3.6 Theranostics is the integration of therapy and diagnostics on a single platform. Green nanoparticles can simultaneously transport therapeutic and imaging chemicals for cancer therapy and monitoring. The Internet of Things can help with real-time tracking of nanoparticle distribution and therapeutic response. Green nanomaterials, such as upconverting nanoparticles, can act as imaging agents and medication carriers.

3.7 Nanorobots: Nanorobots, nanobots, or nanomachines, are extremely small devices or robots designed to work at the nanoscale level. They can be utilized for various activities, including targeted medicine administration, tumor detection, and precision surgery. Nanorobots can be programmed to deliver medications directly to cancer cells, lowering the systemic toxicity associated with traditional chemotherapy. These nanorobots can be programmed to recognize certain cancer cell markers and release therapeutic payloads solely at the tumor site. This method of tailored medication administration improves therapy efficacy while avoiding injury to healthy tissues [18].

3.8 In-Vivo Imaging Nanorobots: Nanorobots can be constructed as microscopic imaging devices to study internal body structures in real time. For example, in diabetes, they can be used to see and assess pancreatic islets to monitor their health and function. This real-time imaging capacity enables early diagnosis and intervention in anomalies. Researchers can create biodegradable nanorobots to make and release insulin when glucose levels exceed a certain threshold. These nanorobots can be programmed to mimic the activity of pancreatic beta cells and assist manage blood sugar levels automatically [19]. Cellular imaging with quantum dots (QDs) has advanced and demonstrated multicolor imaging of labeled cells.

3.9 Smart Tattoos: Researchers have investigated the possibility of "smart tattoos" by employing biodegradable nano-sensors that change color or fluorescence in response to glucose levels. These tattoos can function as non-invasive, wearable glucose monitors, providing real-time input on blood sugar levels. Biodegradable biosensors can be implanted or injected to monitor specific biomarkers associated with diabetic problems, such as kidney function or nerve damage. Continuous monitoring of these indicators may allow for early detection of problems and prompt medical intervention [20]. Figure 2 shows the medical applications of green nanostructures.



**Figure 2**: This diagram depicts the use of smart nano-sensors for monitoring physiological parameters such as pH, glucose levels, external stimuli, and reactive oxygen species (ROS) concentrations [21]**.** (Reproduced with permission).

**4 Nanomaterials in the energy sector:**

Green nanomaterials combined with the Internet of Things (IoT) can revolutionize the energy sector by improving efficiency, sustainability, and monitoring capabilities. The advantages of this integration are as follows:

4.1 Green nanomaterials can improve the efficiency of solar panels, wind turbines, and other renewable energy sources. Nanomaterials, such as quantum dots and nanowires, can improve light absorption and electron transport in solar cells, resulting in higher energy conversion. Furthermore, nanocomposite materials can improve the endurance and strength of wind turbine blades, making them more efficient and reliable [22]. Green nanoparticles can considerably improve energy storage technologies such as batteries and supercapacitors. Nanomaterials can increase the surface area of electrodes, improve ion transport, and improve electrochemical performance.

4.2 Monitoring and Control of Energy Using IoT: Smart meters for real-time energy usage tracking and improving energy infrastructure dependability and efficiency. In urban areas, solar trees with solar panels constructed of green nanomaterials are placed. These IoT-enabled solar trees efficiently harvest solar energy and provide shade, while IoT sensors monitor environmental conditions and regulate energy production accordingly [23].

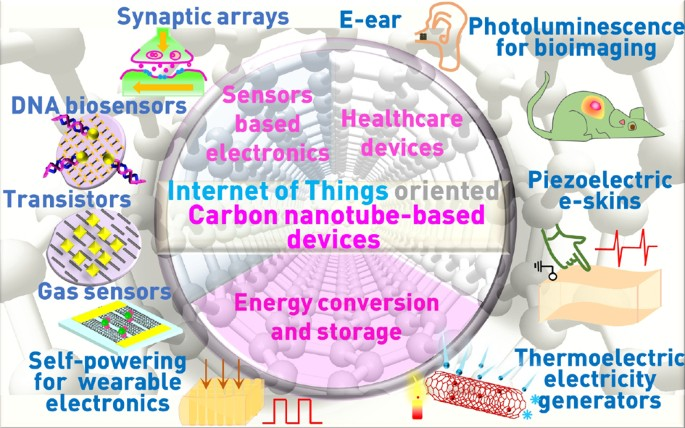
4.3 Smart Buildings and Energy Efficiency: Incorporating green nanomaterials into building components such as windows and coatings improves thermal insulation and energy efficiency. Sensors and controllers based on IoT optimize energy consumption in smart buildings.

4.4 Demand Response and Smart Grid: Green nanomaterials combined with IoT provide smart grid communication, real-time monitoring, and demand response mechanisms, improving grid stability and efficiency. Green nanomaterials, such as piezoelectric nanogenerators and thermoelectric materials, allow ambient energy to be converted into usable electricity. The Internet of Things enables efficient energy scavenging and data-driven energy harvesting systems [24].

4.5 Environmental Impact and Longevity: This section analyses the long-term implications of adopting green nanomaterials combined with IoT in the energy sector to address environmental issues. It addresses potential environmental dangers as well as safety concerns. Green Nanomaterials for Sustainable IoT Devices is a review study that examined several green nanomaterials, such as cellulose nanocrystals, chitosan nanoparticles, and biopolymer-based nanocomposites, and their integration with IoT devices. The study emphasized the eco-friendly production processes of these nanomaterials and their increased environmental performance over conventional materials [25].

4.6 Batteries: Green nanomaterials can be used in modern energy storage technologies such as lithium-ion batteries and supercapacitors. IoT-enabled battery management systems can extend battery life and increase energy storage capacity. IoT sensors combined with AI algorithms may estimate maintenance requirements and detect flaws in energy equipment, saving downtime and optimizing performance. Intelligent feedback systems powered by IoT can analyze real-time data to make informed decisions about catalyst regeneration, reusability, and overall system performance. This closed-loop technique ensures that catalytic reactions stay efficient over long periods [26]. Green nanomaterials like graphene and metal-organic frameworks (MOFs) can be efficient catalysts in hydrogen fuel cell processes. These nanoparticles have a huge surface area and catalytic solid capabilities, allowing for faster and more efficient hydrogen and oxygen conversion into energy. IoT sensors can continuously monitor the operation of the catalyst, allowing for timely replacement or regeneration to maintain optimal efficiency

4.6 Nanomaterials for Hydrogen Storage: Nanomaterials such as metal hydrides and carbon nanotubes can improve hydrogen-keeping capabilities. IoT sensors can monitor hydrogen storage tanks, ensuring safe and efficient storage and informing users when the hydrogen storage media needs replenishment or replacement [27-30]. Green nanotubes with catalytic capabilities can regenerate fuel cells in situ. IoT-enabled tracking devices can identify fuel cell performance degradation and initiate regeneration procedures, extending the overall lifespan of the fuel cells. Nanomaterials can assist fuel cells manage water more efficiently, reducing flooding and enhancing reactant distribution. IoT sensors can monitor real-time water levels and fuel cell settings, assuring peak performance. Energy harvesting is a fundamental component of IoT devices for long-term autonomy. CNTs can gather and convert ambient energy, such as solar or mechanical vibrations, into electrical power. These gathered energy sources can subsequently power low-power Internet of Things (IoT) devices and sensors. The usage of carbon nanotubes is depicted in Figure 3.



**Figure 3:** Illustration demonstrating the use of carbon nanotube-based materials in industrial environments monitored and controlled by IoT devices for energy-efficient automation and seamless communication [28]. (Reproduced with permission).

**5. Conclusion**

This chapter emphasizes how nanomaterials have arisen as innovative instruments with numerous uses in electronics, energy, and healthcare domains. These materials, which have unique properties at the nanoscale, have opened up new avenues for developing innovative technologies and resolving complicated problems. Extensive toxicological and safety analyses should be performed to ensure that green nanoparticles utilized in IoT applications are safe for both human health and the environment. As outlined in the chapter, researchers can create novel and efficient synthesis methods for green nanomaterials by using sustainable and renewable resources. Using green nanomaterials in IoT devices allows for the development of smaller, quicker, and more energy-efficient components in electronics. This paves the way for realizing smart and interconnected systems, which will contribute to advancing smart cities and the Internet of Things ecosystem.

Furthermore, these reduced environmental effects and enhanced recyclability of the material address growing concerns about electronic waste, making devices greener and more sustainable. Continuous health monitoring, early disease identification, and accurate drug administration are all possible with nanoscale sensors and technologies. Using biocompatible and ecologically friendly nanomaterials ensures safer and more sustainable medical practices, propelling healthcare technology and patient care advances. Nanomaterial-based sensors coupled with IoT networks are discussed here that may detect pollutants, monitor air quality, and analyze environmental conditions, assisting in natural resource preservation. Incorporating nanomaterials into IoT-enabled smart farming systems has improved irrigation, crop monitoring, and pest management, resulting in higher agricultural output and less resource waste. Furthermore, nanoparticles have shown promise in water purification because they efficiently remove toxins and pollutants, ensuring clean and safe drinking water for populations. Green nanomaterials combined with IoT enable major gains in energy generation, storage, and management in the energy sector. Nanomaterials with improved electrical conductivity and catalytic characteristics may lead to the development of more efficient solar cells, fuel cells, and energy storage devices. There has been significant study and development in this sector in both Asian and American countries, resulting in several patents, publications, and collaborations. Governments and industry in these locations have recognized the promise of green nanomaterials and IoT and have spent heavily supporting innovation and commercialization. However, there are still obstacles that must be overcome before the full promise of this technology can be realized. Safety and regulatory concerns about nanoparticles in various applications must be thoroughly investigated to ensure consumer and environmental protection. Furthermore, standardization and interoperability challenges in IoT installations must be addressed for smooth integration across platforms and industries. Despite these hurdles, the chapter portrays that the future of green nanomaterials combined with IoT remains bright. It is critical to balance technological innovation and ethical conservation of the environment, ensuring that green nanomaterials and IoT solutions contribute favorably to a cleaner and healthier planet for future generations.

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