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Green nanocomposites for environmental sensors in smart grid systems

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A B S T R A C T

Green nanocomposites are advanced materials that integrate environmentally friendly and sustainable components, such as biopolymers or green-synthesized nanoparticles, to create functional nanomaterials with low toxicity and high eco-compatibility. These materials are increasingly used in environmental sensor technologies due to their enhanced sensitivity, stability, and sustainable synthesis routes. In smart grid systems, green nanocomposites play a crucial role by enabling real-time environmental monitoring with minimal environmental impact, supporting energy efficiency and renewable integration. Smart sensors provide accurate tracking of energy usage trends, enhance load distribution, and advance the sensible application of renewable energy resources. These sensors aid in cutting down on energy waste and by interacting with customers and enabling demand-response systems. Smart grids benefit from sensors made with green nanocomposites for dynamic monitoring of environmental parameters influencing energy generation and consumption. These sensors, embedded in smart home and grid infrastructure, optimize energy efficiency and renewable integration by providing precise data on pollution, temperature, and other conditions. Optimization algorithms in smart grids leverage this sensor data to reduce waste and enhance system reliability. This study demonstrates the role of green nanocomposites in environmental sensors of smart grid systems.

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1. Introduction

Green nanocomposites have advantages such as sustainability, low cost, eco-friendliness, and high performance that biodegradable, renewable, and environmentally benign materials, making them favorable for sustainable development. These nanocomposites typically have high mechanical strength, thermal stability, and other enhanced properties [1, 2]. Green synthesis of nanomaterials for electrochemical sensing is a rapidly growing research area that combines the excellent physicochemical properties of nanomaterials with environmentally friendly and cost-effective green synthesis methods [3, 4]. These green synthetic methods use biological materials such as plant extracts and microorganisms to reduce metal ions into nanomaterials without harsh chemicals. This results in biocompatible, nanocomposites with relatively high strength, stiffness, and low density, suitable for use in sensitive electroanalytical devices [5, 6]. The green nanocomposites are crucial in advancing

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environmentally responsible material science especially in energy devices like solar cells [7], batteries, and LEDs. Green nanocomposites bridge advanced material science and environmental stewardship by employing sustainable manufacturing methods and enabling high-performance, eco-friendly energy devices and sensors, addressing the urgent need to reduce ecological damage from conventional nanotech processes [8, 9]. For example, the conductive nanoparticles into insulating polymer matrices forms nanocomposites that exhibit a piezoresistive effect, which is highly useful for sensing applications [10].

When the concentration of conductive nanoparticles reaches a critical level, called the percolation threshold, a continuous conductive network forms, leading to a significant increase in electrical conductivity. This percolation phenomenon is well documented and fundamental to the function of these sensors [11]. Eco-friendly synthesis of sensors, especially nanocomposite sensors, has become a prominent focus for practical environmental remediation in recent years. Sensors function as energy converters that detect physical, chemical, or mechanical changes in the environment and convert them into electrical or optical signals [12]. This mini review aims to include the use of green nanocomposites in environmental sensors and how they can be used in smart grid systems.

2. Overview of green nanomaterials and green nanocomposites

Nanomaterials have rapidly become integral across many sectors due to their unique size-dependent properties. They find overwhelming applications in electronics, sensors, and biomedical fields by enabling devices with enhanced sensitivities, tunable properties, and multifunctionality. Researchers constantly seek newer synthesis methods that allow more efficient, controlled preparation, which helps in fine-tuning nanomaterial properties for specific applications [12]. Nanocomposites, especially green nanocomposites, are widely used nanomaterials characterized by their sustainability, light weight, cost-effectiveness, and environmental friendliness. These green nanocomposites are primarily derived from plant fibers which serve as natural fillers. A unique feature of green nanocomposites is the ability to tailor material properties by selecting appropriate matrix-filler combinations and mixing them in suitable ratios. Such combinations provide customizable properties for various applications [13]. The synthesis technique selected for nanocomposites is crucial because different methods offer unique features that affect the properties and applications of the final material [14]. The design, production, application, and disposal of natural nanocomposites garner significant interest due to their environmental advantages. Natural nanocomposites typically involve renewable natural polymers like chitosan, chitin [15], starch (from corn, potato, yuca, etc.), glucose, cotton, cellulose and derivatives, natural fibers, and natural rubber. These materials emphasize green, environmentally friendly alternatives over traditional synthetic counterparts [16].

When these green nanomaterials are combined with other materials to form composites using eco-friendly synthesis routes, they are referred to as green nanocomposites. Such green nanocomposites reflect sustainability not only in their individual components but also in their overall production and application processes [17]. A nanocomposite is a multiphase solid material where at least one phase has dimensions under 100 nm or contains nanoscale structural repeats.

It typically consists of a bulk matrix combined with nanoscale phases that differ in structural and chemical properties, leading to unique material characteristics [18]. Nanocomposites exhibit a broad range of enhanced properties including superior mechanical strength, electrical and thermal conductivity, optical clarity, electrochemical behavior, catalytic activity, and barrier performance against gases and moisture. These improvements result from the nanoscale fillers incorporated within the matrix, which create mechanisms like enhanced interfacial bonding, increased surface area, and tortuous paths that impede gas diffusion [19]. Various synthesis methods widely used and suitable for the preparation of nanocomposites. Nanocomposite, in general, can be classified into three broad categories namely (i) polymer matrix nanocomposites, (ii) ceramic matrix nanocomposites, and (iii) metal matrix nanocomposites [20].

3. Overview of environmental sensors

Technological advancement, particularly in fields like the Internet of Things (IOTs) and various communication methods have emerged, and sensor technologies have also reached a developed level and are widely used [21]. The natural environment has been gradually polluted by events such as climate warming and pollution emissions, and the demands of modern human beings for life safety and quality of life conflict with the declining quality of the natural environment and natural resources. Ordinary environmental monitoring methods, such as physical deployment of monitors to conduct sampling, are described as cumbersome, inefficient, and costly [22]. Wireless network technology advancements combined with sensor miniaturization have enabled realistic and practical monitoring of the natural environment through wireless sensor networks. These networks consist of an array of small sensor nodes that collectively sense environmental parameters (such as humidity, temperature, pressure) and transmit the data wirelessly to a central server or data repository for real-time or later analysis. operate by communicating among sensor nodes and forwarding collected data via a sink or gateway node connected to a server, often accessible over the internet [23]. Collected information on Sandia-developed sensor technologies applicable to monitoring contaminants including trace metals, radioisotopes, volatile organic compounds (VOCs), and biological pathogens [24]. Advanced science and technology play a crucial role in real-time environmental monitoring systems that measure air quality, water quality, and other vital indicators to control pollution levels and ensure the safety of humans and wildlife. Key technologies include IoT-enabled sensors, satellite-based remote sensing, artificial intelligence (AI), and blockchain systems, which together enable continuous, automated data collection, processing, and predictive modeling for sustainable resource management [22].

3.1. Types of environmental sensors

Environmental sensors are indeed connected devices capable of providing diverse types of information such as location, position, individual movements, and contextual elements [25]. These data can be compared with information collected from sensors embedded on or implanted in individuals to validate alarms, such as fall detection. However, their deployment raises significant ethical concerns primarily related to privacy and surveillance [25, 26]. The point about sensitivity is indeed critical for video capture sensors, especially when these sensors are used in robotic devices to interact with humans. Such sensors must be highly sensitive to accurately capture visual information and adapt to the context or needs of the person they are interacting with. This sensitivity enables the sensor to detect subtle changes and provide real-time data to the robotic system, allowing it to modify its behavior or responses accordingly. Video capture sensors in robotic applications are often part of a larger sensory system that includes tactile, thermal, and motion sensors, enabling comprehensive interaction capabilities including adapting to human gestures, expressions, and environmental context [27]. Environmental sensors like air quality sensors, light sensors, and smoke detectors typically do not have the primary objective of monitoring individual health. However, the data these sensors collect can be cross-referenced with other data sources to produce potentially personalized health information and trigger alarms for health-related changes [28]. Table 1 lists the types of sensors and their characteristics.

4. Green nanocomposite materials in environmental sensor technologies

Nano sensors operate by monitoring physicochemical changes caused by the target analyte's interaction with the sensor surface, often leading to electrical, optical, or other transduced signals [36]. Nanosensors consist of a recognition component that enhances specificity and a signal transmission system that outputs electrical or optical signals, enabling real-time, sensitive, and selective pollutant detection [37]. Due to their nanoscale size and high surface-to-volume ratio, nanosensors have enhanced sensitivity, selectivity, and speed compared to conventional sensors [38]. These qualities allow nanosensors to detect single molecules and monitor various physical properties such as pressure, temperature, concentration, and more and find applications in diverse fields including medicine, environmental monitoring, pollution control, and pathogen detection, among others [12, 39]. Green nanomaterials have emerged as highly effective nanosensors in environmental monitoring [40], enabling the sensitive detection and removal of various pollutants such as toxic gases, heavy metals, and organic contaminants even at extremely low concentrations ranging from nanomolar to sub-picomolar levels [41]. Nanowires and other nanomaterials revolutionized sensor creation starting in the early 2000s by enabling very sensitive and specific detection of chemical, biological, and physical parameters such as temperature and pressure [42]. Nanowires offer advantages like high surface-to-volume ratios and enhanced electrical properties that improve sensing performance. Their applications include chemical and biosensors capable of detecting extremely low concentrations of analytes and physical parameters with high precision [43]. The development of nanowire sensors has involved various materials (metallic, semiconducting, insulating) and fabrication methods, significantly advancing sensor technologies and enabling applications in diverse fields including environmental monitoring, healthcare, and industrial uses [44]. Au-based eco-friendly nanocomposites are recognized for their unique surface and electronic properties that make them highly promising for sensing applications, specifically in environmental monitoring and biomedical diagnostics [45]. These nanocomposites, when combined with biocompatible and biodegradable materials such as starch, enhance mechanical robustness, electrical conductivity, and flexibility, facilitating their use in wearable and transient electronics for sustainable environmental sensors [46]. For instance, starch-based nanocomposites reinforced with gold (Au), cadmium sulfide (CdS), or MXene exemplify transient electronics with improved mechanical and electrical performance, suitable for flexible sensors sensitive to movements or touch. Such materials contribute to the development of sustainable, eco-friendly sensor devices that meet the demands of durability, flexibility, and sensitivity [47].

Vinod Patil et al. [48] proposed a smart grid model design integrating renewable energy resources including solar panels, windmills, and hydraulic power plants, aiming to create energy-efficient smart grid systems that reduce greenhouse gas emissions and enhance network lifetime. Other research groups have reported green synthesis of metal/polymer nanocomposite particles which have applications in catalytic reactions and potentially in smart materials for energy systems [49]. Green composites are used to enhance the performance of supercapacitors and lithium-ion batteries, which are crucial for balancing supply and demand in smart grids [50, 51]. Fig. 1 and 2 show the hardware and software used for the general block diagram of smart the experiment and the general block diagram of smart water quality monitoring system [52, 53].

5. Smart grid relevance environmental sensors

Smart sensors integrated into smart grid systems can enhance environmental monitoring by continuously tracking parameters such as temperature, humidity, and air quality, thereby enabling proactive and timely responses to environmental changes [54]. Safety applications such as detecting partial discharges in power devices are critical for preventing energy losses and enhancing grid reliability. Partial discharge detection helps identify early insulation defects in power equipment like transformers, cables, and switchgear, enabling timely maintenance interventions and avoiding catastrophic failures and reduces equipment failure rates, improves power supply stability, and supports preventive maintenance, thereby significantly enhancing the reliability and safety of power grids [55]. Intelligent resource management using fuzzy inference systems (FIS) demonstrates strong capability in optimizing energy consumption and enhancing user comfort. Studies have shown that fuzzy logic integrated with other techniques can optimize energy use in residential buildings by adjusting factors like lighting, heating, and cooling systems based on environmental and occupancy data. This leads to significant energy savings while maintaining or improving comfort levels for occupants [54]. The integration of AI within smart sensor systems thus amplifies benefits and is shaping the future of smart, connected environments with enhanced predictive, diagnostic, and security capabilities [56].

Table 1
Types of environmental sensors

Sensor type	Applications	Measured parameter	Ref.
Temperature	Weather stations, HVAC systems, agriculture	Ambient temperature	[29]
Humidity	Greenhouses, smart homes, industrial processes	Relative humidity	[24]
Air	Urban monitoring, indoor air quality, vehicles	Pollutants (e.g., CO_2, PM2.5)	[30]
Pressure	Meteorology, altimeters, aviation	Atmospheric pressure	[31]
Light	Smart lighting, solar tracking, photography	Light intensity, UV index	[31]
Soil	Precision farming, irrigation systems	Volumetric water content	[31]
Rain	Presence or amount of rainfall	Weather stations, irrigation	[32]
Gas	Industrial safety, leak detection, mining	Specific gases (e.g., methane), CO_2, NOx, SO_2, O_3, VOCs	[33]
UV	Ultraviolet radiation levels	Health monitoring, environmental studies	[34]
Sound	Noise levels	Noise pollution monitoring	[35]
Radiation	Ionizing radiation	Nuclear facilities, Ionizing radiation levels	[24]

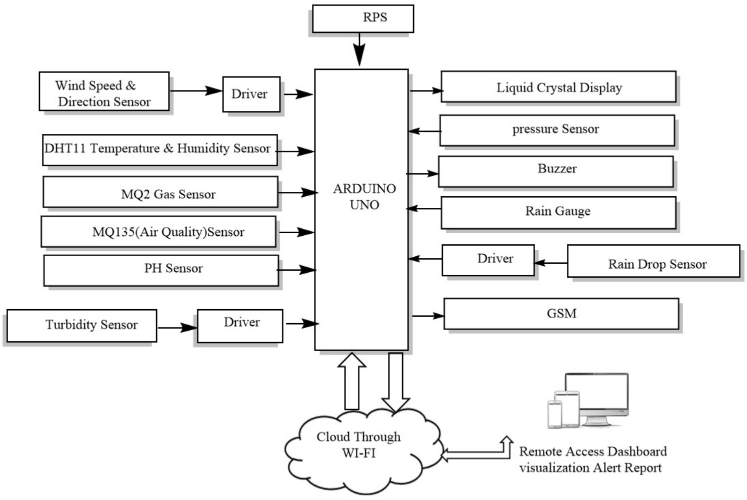

Fig. 1. Taxonomy diagram of general quality monitoring system.

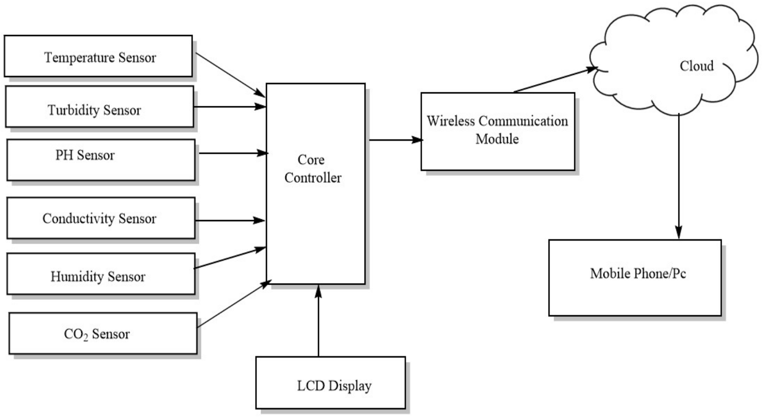

Fig. 2. Taxonomy diagram of water quality monitoring system.

Smart grid sensors play a critical role in environmental sustainability by enabling real-time monitoring and optimization of energy flows, which reduces transmission losses and minimizes energy waste, thereby lowering carbon footprints [57]. These sensors also facilitate the integration of renewable energy sources like solar and wind by dynamically adjusting energy distribution to handle their variability, ensuring a stable and reliable supply while reducing dependence on fossil fuels. Additionally, smart grid sensors enhance demand response and load management, optimizing energy supply based on consumption patterns to avoid overproduction and energy waste. They empower consumers with real-time insights into their energy use, fostering more sustainable consumption behaviors [58]. Additionally, Smart grids play a crucial role in the seamless integration of renewable energy sources such as solar and wind into the electricity grid. By dynamically managing and adjusting energy distribution to accommodate the variability and intermittency inherent in these renewable sources, smart grids ensure a stable and reliable power supply. This reduces reliance on non-renewable resources and supports a more sustainable energy system [59]. Smart grid sensors significantly enhance demand response and load management capabilities by enabling real-time adjustment of energy supply based on consumption patterns. This real-time data monitoring allows the grid to optimize energy distribution, reducing overproduction and minimizing energy wastage, which results in more sustainable and efficient resource use [60]. These technologies empower consumers by providing them with real-time insights into their energy usage, encouraging informed decision-making and fostering sustainable consumption practices [59]. Therefore, smart grid sensors are essential to improve the resilience, efficiency, and reliability of power systems [59]. These sensors support technologies for real-time grid management, fault detection, energy optimization, smart metering for consumer engagement and conservation, and integration of renewable energy to enhance sustainability. Advances incorporate AI and IoT to enhance fault detection and optimization [61]. Smart grid technology enhances environmental sustainability by improving energy efficiency, facilitating renewable energy integration, and enabling consumer engagement [62]. The addition of intelligent sensors to smart grids is crucial as they provide real-time monitoring and optimization of energy flows, helping reduce transmission losses and energy waste, thus lowering carbon emissions. These sensors also dynamically adjust energy distribution to accommodate the variability of renewable sources like solar and wind, which increases system efficiency and reduces reliance on fossil fuels. Moreover, they enable demand response and load management by adjusting supply based on consumption patterns, optimizing resource use, and empowering consumers with real-time energy usage insights to foster sustainable consumption habits. Through these mechanisms, smart grid sensors support reducing greenhouse gas emissions and water usage, advancing overall environmental sustainability efforts in energy systems [54].

This impacts the energy sector is undergoing a significant transition from large-scale central production to decentralized, local energy generation primarily using renewable energy sources and distributed energy resources [63]. This shift aims to make the electric system more intelligent by integrating new energy technologies, enabling more flexible, resilient, and sustainable energy management [64]. Decentralized energy production includes technologies such as rooftop solar panels, small wind turbines, battery energy storage, and microgrids, which reduce reliance on fossil fuels, transmission losses, and support grid decarbonization. The innovation and integration of smart technologies like IOT, smart inverters, and energy management systems are key to supporting this evolution toward smart grids and smart homes, aiming to optimize energy use and reduce the sector's environmental footprint [62].

6. Challenges and future directions

Green nanocomposites for environmental sensors in smart grid systems indeed face multiple challenges in technical implementation, economic feasibility, and scalability. However, their future potential is promising with key future directions including integration of AI, innovations in green synthesis methods, improved material design, and decentralized control mechanisms to enhance sustainable and efficient smart grids [65]. Advancing green synthesis routes and eco-friendly approaches for producing sustainable nanomaterials and nanocomposites, including graphene and biopolymers, focuses on using environmentally benign, cost-effective, and sustainable materials and methods to minimize environmental impact [66, 67].

7. Conclusion

Smart grid sensors are key enablers for a sustainable energy future. Their strategic deployment combined with AI integration can help meet energy demands while promoting long-term environmental and economic sustainability, especially as nations transition to greener power infrastructure. These sensors enhance environmental sustainability by improving renewable energy integration, reducing transmission losses, enabling real-time fault detection, optimizing load management, and promoting active consumer participation in energy saving. They reduce fossil fuel dependency and improve demand-response mechanisms to stabilize the energy supply and consumption. These sensors enhance environmental sustainability by improving renewable energy integration, reducing transmission losses, enabling real-time fault detection, optimizing load management, and promoting active consumer participation in energy saving. They reduce fossil fuel dependency and improve demand-response mechanisms to stabilize the energy supply and consumption. Thus, environmental sensors in smart grids are critical for promoting energy conservation, integrating clean energy, ensuring system reliability, and supporting environmental monitoring and sustainability initiatives across urban and industrial settings.

Author contributions

Fatemeh Heidari: Conceptualization, Writing – original draft, Writing – review & editing; **Zahra Salimi:** Writing – review & editing, Supervision**; Fateme Moradi:** Writing – original draft, Writing – review & editing.

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Conflict of interest

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Data availability

No data is available.

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