**Original Research Article**

**AI-Driven Integration of Nanotechnology and Green Nanotechnology for Sustainable Energy and Environmental Remediation**

**ABSTRACT**

This research critically examines the synergistic integration of nanotechnology and green nanotechnology as a disruptive framework for addressing dual imperatives of sustainable environmental remediation and next-generation clean energy systems. By exploiting the physicochemical uniqueness of nanomaterials- such as quantum confinement, surface plasmon resonance, enhanced electron mobility, and high surface-to-volume ratios- this study elucidates the multifaceted mechanisms by which engineered nanomaterials (ENMs) facilitate the adsorption, catalysis, degradation, and real-time sensing of diverse pollutants across air, water, and soil matrices. Importantly, these processes are governed by the foundational principles of green chemistry and sustainable engineering, prioritizing biogenic synthesis, non-toxic precursors, low-energy fabrication, and end-of-life biodegradability to mitigate ecological and health risks. The study further explores how nanostructured components- including perovskite nanocrystals, quantum dots, plasmonic nanoparticles, and nanocomposites- redefine the performance boundaries of photovoltaic cells, fuel cells, thermoelectric generators, and electrochemical storage devices. The convergence of nanogenerators (TENGs, PENGs), nano-enabled supercapacitors, and AI-optimized hybrid energy modules is shown to enable continuous, resilient, and decentralized electricity generation, particularly in climate-vulnerable and off-grid regions. A novel AI-augmented architecture incorporating nano-sensors, edge computing, and digital twins is proposed to facilitate predictive diagnostics, adaptive control, and lifecycle optimization of these intelligent energy ecosystems. Moreover, a comprehensive cradle-to-grave life cycle sustainability assessment (LCSA) evaluates carbon intensity, energy return on investment (EROI), nanotoxicological profiles, recyclability, and circularity potential. This ensures that technological advancement aligns with planetary boundaries and long-term ecological integrity. The research underscores the ethical imperative of responsible innovation, advocating for regulatory convergence, precautionary design, and stakeholder-inclusive deployment strategies. By fusing material science, environmental engineering, artificial intelligence, and sustainability science, this study presents a cutting-edge, multidisciplinary roadmap for leveraging nanotechnology and green nanotechnology as accelerators of global ecological restoration and clean energy transition.

**KEYWORDS**

Artificial Intelligence, Clean Energy Technologies, Green Nanotechnology, Life Cycle Assessment (LCA), Nanomaterials, Nanotechnology, Sustainable Development, Sustainable Environmental Remediation, Waste-to-Energy Systems.

**INTRODUCTION**

Innovative and multidisciplinary approaches are required to address the interconnected global problems of increasing environmental deterioration and the pressing need for sustainable energy alternatives. The manipulation of matter at the nanoscale (1–100 nm), or nanotechnology, has become a promising topic with special physicochemical qualities for a range of uses, such as energy production and environmental remediation (Whitesides, 2004). At the same time, green nanotechnology has emerged as a result of increased awareness of the negative environmental effects of traditional industrial methods. In order to reduce the environmental impact of the production, use, and disposal of nanomaterials, this developing paradigm incorporates the ideas of sustainable engineering and green chemistry (Anastas & Warner, 2000). The potential for developing game-changing solutions for a more sustainable future is enormous when these two powerhouse fields come together. Researchers are investigating new approaches for effective pollutant removal from diverse environmental matrices and the development of cleaner, more efficient energy systems by carefully fusing the improved functionality provided by nanomaterials with environmentally friendly techniques. The synergistic opportunities brought about by this convergence will be examined in this introduction, along with their importance in tackling pressing energy and environmental issues and opening the door to a more environmentally friendly global ecosystem.

The enabling technology that works with materials that are nanometers in size is called nanotechnology. Nanotechnology is expected to become established at multiple levels, including materials, electronics, and systems. As far as scientific understanding and commercial applications are concerned, the nanomaterials level is now the most inventive. In recent decades, nanotechnology has been regarded as an applied technology in many different fields. The convergence of several fields has produced nanotechnology, which offers a means of working at the atomic level and producing novel structures. The creation of materials and devices at the nanoscale and their manipulation to harness their special properties are both included in nanotechnology. The environment is one field in which nanotechnology can be applied. We will be able to swiftly and precisely identify and track the consequences of human activity on the environment thanks to nano-sensors. According to Taran et al. (2020), nanotechnology aids in the reduction of current pollutants and the efficient use of our resources. Applying nanotechnology will increase the efficiency of clean energy production. For example, solar cells, wind, sea, and geothermal energy can produce much energy efficiently using nanomaterials, and fossil energy will be replaced by renewable energy. Nanotechnology has caused the material to be consumed in a way that it effectively reduces the entry of pollutants, resulting from human activities, to the environment (Taran et al., 2020). The term "green nanotechnology" describes the application of nanotechnology to enhance the inherent stability of processes that generate harmful external chemicals. It also refers to the application of items made using nanotechnology to enhance sustainability. It entails producing unprocessed nanoproducts and applying them to promote sustainability. Green nanotechnology is defined as the advancement of clean technology, lowering the possible risks to the environment and human health that come with the manufacture and application of nanotechnology products, and encouraging the substitution of new, ecologically friendly nanoproducts for current ones over the course of their life cycles (Garcia, 2022).

The capacity to see nanoparticles has created a plethora of opportunities in several scientific and industrial fields. It can have a wide range of uses since it is just a collection of methods that enable property manipulation at a very tiny scale. It offers numerous benefits in a variety of fields, including the food industry (for improved food production), the medical (nano medicine), the apparel (fabric), the environment (e.g., water purification systems), privacy and security (nano electronics), fuel cells, solar cells, fuels, sporting goods, etc. Thus, it has a lot of benefits, is accelerating, and has many individuals conversing (K & V, 2017). While it is true that nanotechnology has greatly benefited the globe, there are also some drawbacks to this technology. Only a few characteristics, particularly their mobility and heightened reactivity, can make nanomaterials dangerous; their mere existence is not a threat in and of itself. Only specific characteristics of specific nanoparticles posed a real risk to the environment or to living things. It may be referred to as micro pollution in this instance. This merely serves to highlight the reality that everything has advantages and disadvantages and that nothing is flawless (K & V, 2017). In order to reduce climate change and promote a more environmentally friendly global ecosystem, it is critical to create efficient and sustainable clean energy producing technologies. Particularly when combined with the ideas of green chemistry, nanotechnology provides novel techniques to improve the efficiency and lessen the environmental impact of renewable energy sources. Green nanotechnology reduces the environmental impact of nanotechnology applications by combining the concepts of green chemistry and nanoscience. In order to produce nanomaterials that support environmental sustainability, renewable resources, energy-efficient manufacturing techniques, and non-toxic materials are used. Green nanotechnology seeks to improve the functionality and efficiency of nanomaterials while minimizing the use of dangerous chemicals, cutting down on energy use, and reducing waste production (Navyashree et al., 2025). Figure 1 illustrates how nanotechnology can be applied in the environment.

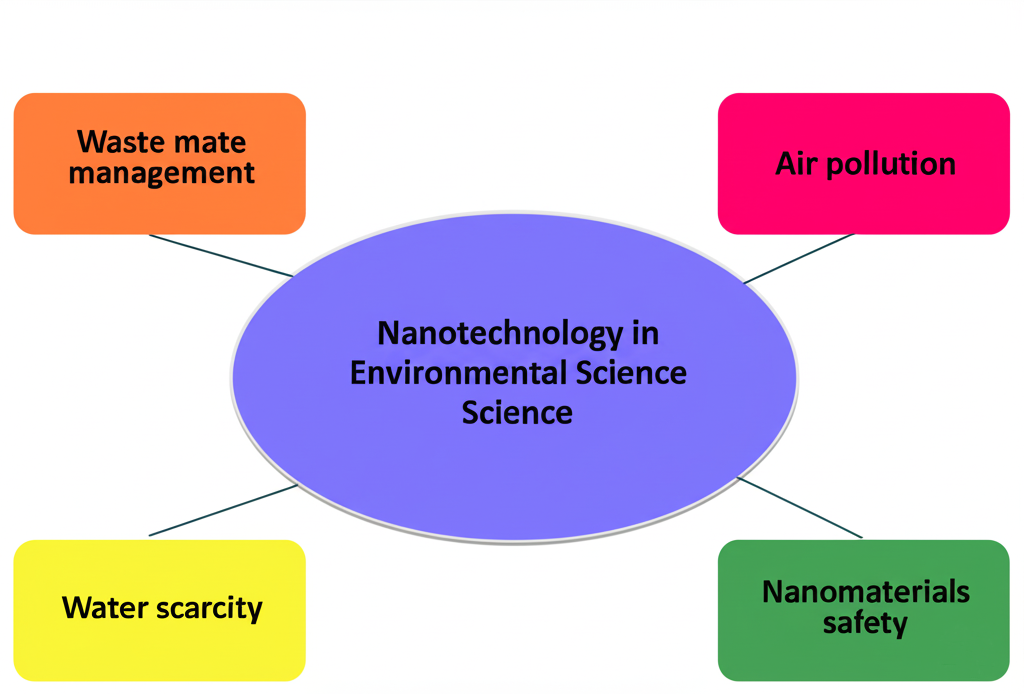


Figure 1: Environmental Science makes significant use of nanotechnology (Source: Taran et al., 2020).

**LITERATURE REVIEW**

Innovative and sustainable solutions are required to address the growing environmental problems facing the world, such as pollution and climate change (Islam, 2025). With its distinct material properties at the nanoscale, nanotechnology presents a promising solution to these problems. At the same time, the sustainability of these technical developments depends on adhering to the principles of green nanotechnology, which are centered on reducing the environmental impact of nanomaterials throughout their lifecycle (Anastas & Warner, 1998). The combination of these two domains signifies a significant paradigm change in the direction of creating safe and efficient solutions for clean energy production and environmental remediation (Islam, 2025). The purpose of this literature review is to examine the most important discoveries, recent advancements, and potential paths in this multidisciplinary field. Nanomaterials have proven to be incredibly effective at eliminating a wide range of contaminants from diverse environmental matrices. Effective adsorption, catalytic degradation, and pollutant detection are made possible by their high surface area to volume ratio, improved reactivity, and adjustable surface functions. The remediation of heavy metals, organic pollutants, and newly discovered contaminants in water, soil, and air has been studied using nanoparticles, nanotubes, nanowires, and nanocomposites.

Although nanotechnology provides answers, the effects of producing and using nanomaterials on the environment are a serious worry. This is addressed by green nanotechnology, which minimizes waste production, uses bio-based precursors, and concentrates on sustainable synthesis pathways. This field of study encompasses the creation of biogenic nanoparticles, the use of safe solvents, and the creation of nanomaterials that are naturally recyclable or biodegradable (Vance et al., 2015). The long-term viability of nano-enabled remediation methods depends on the combination of high-performance nanomaterials and green synthesis techniques. Nanomaterials are essential for improving the sustainability and efficiency of several clean energy technologies. Nanomaterials are employed in solar cells to enhance energy conversion and light absorption (Grätzel, 2001). They work as catalysts with increased durability and activity in fuel cells. In order to achieve greater energy density and quicker charging rates, nanostructured materials are also essential for new battery technologies (Armand & Tarascon, 2008). The use of ecologically friendly materials and production techniques is the main emphasis of the application of green nanotechnology principles in the creation of clean energy technologies. Low-energy production methods, the use of abundant and non-toxic materials, and the creation of gadgets with a low lifetime environmental effect are all examples of this (Fthenakis et al., 2008). Figure 2 below illustrates the many kinds of nanomaterials used in nanoremediation.

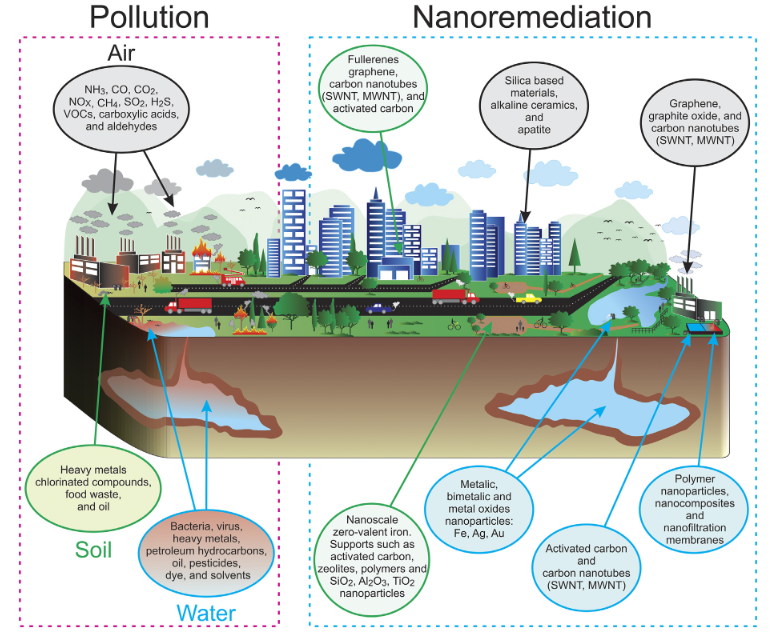


Figure 2: For nano remediation, a variety of nanomaterials are used (Figure Source: Del Prado-Audelo et al., 2021b).

The effects of nanoparticles employed in energy and remediation applications on the environment and human health must also be included in a thorough literature evaluation. For assessing these technologies' overall sustainability, life cycle assessment (LCA) studies are essential. Furthermore, responsible innovation depends on comprehending and reducing the possible dangers connected to exposure to nanomaterials (Nel et al., 2006). The fields of green nanotechnology and convergent nanotechnology are developing quickly. The creation of multipurpose nanomaterials, the expansion of environmentally friendly synthesis and application methods, and the creation of strong regulatory frameworks are some future research avenues. It will be essential to address the issues of affordability, stability over the long run, and public opinion if these promising technologies are to be widely adopted.

**METHODOLOGY**

The methodology underpinning this critical examination of AI-driven integration in nanotechnology for sustainable energy and environmental remediation is anchored in a highly interdisciplinary and forward-looking scientific framework. It commences with the **conception and modeling of a novel AI-augmented system architecture,** which is engineered to seamlessly integrate real-time data from cutting-edge nano-sensors with a dynamic digital twin framework. This architectural blueprint is fundamentally designed to facilitate unprecedented levels of predictive diagnostics, adaptive control, and comprehensive lifecycle optimization across diverse nanotech-enabled systems. Specifically, this involves the **development and strategic deployment of highly sensitive and selective nano-sensor arrays,** leveraging advanced plasmonic, electrochemical, and quantum dot-based modalities for precise, in-situ monitoring of critical environmental parameters—such as pollutant concentrations and redox potential—alongside key energy system performance indicators, including charge-discharge cycling stability and degradation kinetics. Data fidelity and real-time responsiveness are further ensured through the **integration of edge computing**, where robust algorithms perform preliminary data pre-processing, anomaly detection, and rapid analytical computations directly at the source, thereby minimizing latency and optimizing bandwidth. Concurrently, a **high-fidelity digital twin of the target system-** be it an advanced photocatalytic reactor for wastewater purification or a next-generation solid-state battery array- is meticulously constructed. This digital twin is not merely a static representation but a living computational model, incorporating intricate multi-physics simulations, including computational fluid dynamics, detailed reaction kinetics, and advanced electrochemistry, all dynamically updating their states based on the live data streams from the nano-sensor networks, thereby enabling precise, real-time simulation of system behavior under a myriad of operational conditions.

Further advancing the scientific rigor, the methodology extends to the **innovative design, synthesis, and exhaustive characterization of advanced nanomaterials.** This begins with **computational material design (CMD),** employing ab initio techniques such as Density Functional Theory (DFT) and Molecular Dynamics (MD) simulations to predict with atomistic precision the electronic band structures, surface reactivity, and adsorption mechanisms of bespoke nanostructures, including pioneering transition metal dichalcogenides, tailored perovskite nanocrystals, and high-performance single-atom catalysts, thereby guiding the rational design of materials with precisely tuned properties. This is powerfully augmented by Machine Learning (ML) Accelerated Materials Discovery, where high-throughput virtual screening of expansive material databases is coupled with active learning algorithms to drastically expedite the identification of optimal candidate nanomaterials exhibiting superior photocatalytic efficiencies, charge transport kinetics, or enhanced adsorption capacities. Complementing this, an unwavering commitment to sustainability is embodied through **advanced green synthesis methodologies.** This encompasses the exploration of highly scalable and environmentally benign biogenic synthesis routes utilizing microbial and plant-mediated pathways for metallic nanoparticles and metal oxides, significantly reducing hazardous byproducts. Furthermore, the use of supercritical fluid synthesis leverages eco-friendly solvents like supercritical CO2 for precise morphological control and size distribution of nanomaterials, mitigating the reliance on conventional, toxic organic solvents. Post-synthesis, rigorous **physicochemical characterization** is paramount, employing cutting-edge techniques such as High-Resolution Transmission Electron Microscopy (HR-TEM) and Scanning Electron Microscopy (SEM) for atomic-scale morphological analysis, X-ray Diffraction (XRD) and X-ray Photoelectron Spectroscopy (XPS) for crystalline phase identification and surface chemistry, alongside advanced spectroscopic and electrochemical methods to elucidate optical, electronic, and charge transfer properties critical for their intended energy and environmental applications.

At the very core of this integrated approach lies the **development and sophisticated training of advanced AI models for predictive control and dynamic optimization.** This process necessitates the **meticulous acquisition and pre-processing of heterogeneous datasets,** drawing from real-time nano-sensor outputs, high-fidelity digital twin simulations, and extensive historical experimental data, followed by robust data cleaning, normalization, and intelligent feature engineering to optimize data quality for AI model training. The **selection of machine learning algorithms** is strategically tailored to specific challenges: Deep Learning (DL) architectures, including Convolutional Neural Networks (CNNs) for pattern recognition in material degradation and Recurrent Neural Networks (RNNs) or Long Short-Term Memory (LSTM) networks for predictive time-series analysis of system performance, are employed. Crucially, **Reinforcement Learning (RL) algorithms** are developed to enable autonomous learning of optimal control strategies for dynamic system operation, for instance, adaptively adjusting photocatalytic lamp intensities or optimizing energy storage charging/discharging protocols, to maximize efficiency and operational longevity under fluctuating environmental conditions. A groundbreaking aspect involves the incorporation of Physics-Informed Neural Networks (PINNs), which embed fundamental physical laws directly into the neural network architecture, thereby enhancing model generalization, minimizing data dependency, and ensuring the physical consistency of all predictions. Rigorous **model training and validation** are performed using advanced optimizers and k-fold cross-validation, with performance rigorously assessed via metrics such as Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and standard classification metrics. Finally, the integration of Explainable AI (XAI) techniques, such as SHAP values and LIME, ensures interpretability of complex AI model decisions, fostering transparency and building trust in the system's recommendations, which is paramount for critical applications within the energy and environmental sectors.

The ultimate validation of this integrated nanotechnology-AI system hinges upon a **comprehensive performance evaluation.** For energy applications, this encompasses quantifying power conversion efficiency, specific capacity, energy and power densities, alongside crucial cycling stability and degradation rates over extended operational periods. In environmental remediation, key metrics include pollutant removal efficiency, mineralization rates, treatment time, and the long-term reusability and stability of the nanomaterials. The **AI model performance** is assessed not only by its predictive accuracy but also by its real-time responsiveness and its proactive ability to identify optimal operational parameters and anticipate potential system failures. Critically, a **holistic Life Cycle Assessment (LCA),** rigorously compliant with ISO 14040/14044 standards, is conducted to quantify the environmental footprint of the entire system, from the initial nanomaterial synthesis through to end-of-life considerations, encompassing energy consumption, greenhouse gas emissions, water usage, and potential toxicity profiles. This comprehensive LCA serves as a vital validation of the inherent "green" principles embedded within the proposed integrated framework, affirming its contribution to truly sustainable solutions.

**NANOTECHNOLOGY**

Nanotechnology, or the manipulation of matter at the nanoscale (1-100 nanometers), is a rapidly developing field with significant implications across a variety of sectors. It is no longer a future idea. Its capacity to design materials and gadgets with unique characteristics has sparked advancements in electronics, materials science, energy, and medicine. New developments keep expanding the realm of what is feasible on this extremely small scale. Nanotechnology is still being used by the electronics sector to produce gadgets that are quicker, smaller, and use less energy (AZoNano, 2024). Nanoscale semiconductors called quantum dots are improving display technologies by adding more energy efficiency and vivid colors (He, 2023). Additionally, developments in nanoelectronics are opening the door for data storage and computing solutions of the future. Additionally, the energy sector is reaping substantial benefits (Wikipedia authors, 2024). Nan catalysts are boosting the efficiency of fuel cells and solar cells, contributing to cleaner energy production (Omeiza et al., 2023). Additionally, nanomaterials are being investigated for improved energy storage in super capacitors and batteries (Mohammed, H., et al., 2025). Despite nanotechnology's enormous promise, responsible development and rigorous evaluation of its possible effects on the environment and human health continue to be critical areas of study. Because of their high surface area and reactivity, nonmaterial’s provide improved contaminant removal from soil, water, and air, facilitating more effective environmental cleanup. Real-time monitoring of contaminants by nanosensors enables prompt identification and remediation of environmental contamination. In an effort to stop pollution at its source, nanotechnology helps create more sustainable materials and cleaner industrial processes.

**GREEN NANOTECHNOLOGY**

The goal of the developing discipline of "green nanotechnology" is to maximize the advantages of nanotechnology while reducing the hazards to the environment and human health (Insight 1: Green Nanotechnology Enhancements in Manufacturing Sustainability, n.d.). It designs, produces, and uses nanomaterials and products using the concepts of green chemistry and green engineering. The role of green nanotechnology in bioremediation and preventing environmental contamination is depicted in Figure 3 below.

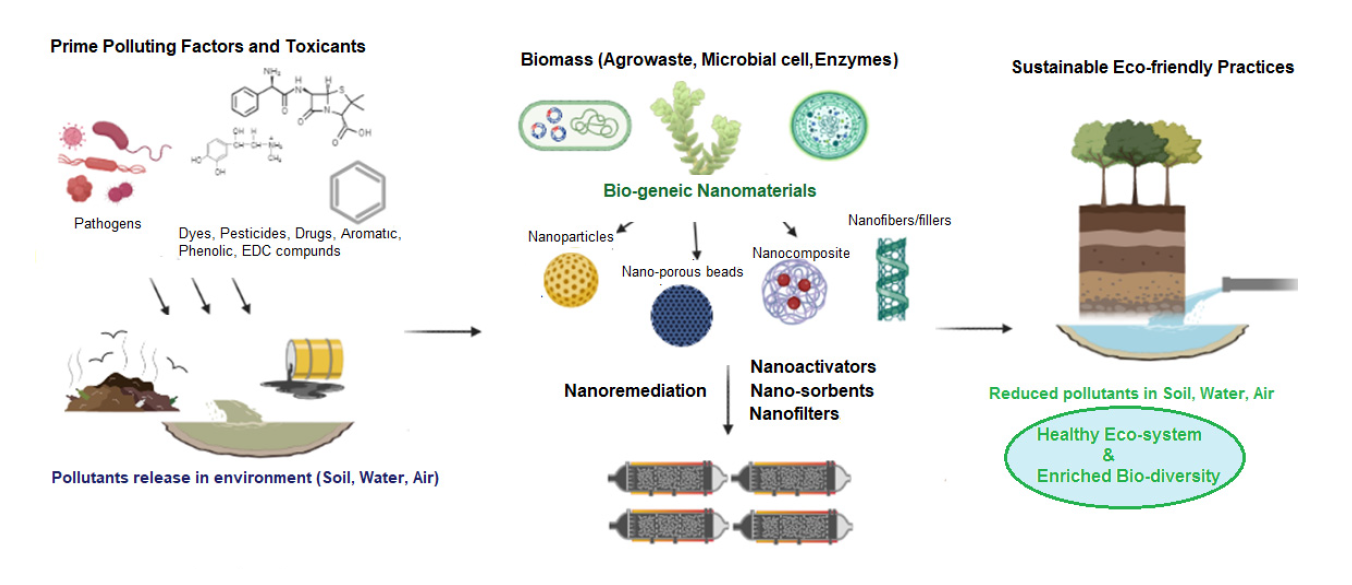


Figure 3: Green nanotechnology's function in environmental pollution prevention and bioremediation (Figure Source: Bhandari et al., 2023).

The goal of this strategy is to develop long-term fixes for a range of environmental problems (Narayanan et al., 2024). Creating environmentally friendly synthesis techniques, such as creating nanoparticles from biological systems like plant extracts, is one important component. This lessens the need for energy-intensive processes and hazardous chemicals. Developing intrinsically safer nanoparticles and products while taking into account their full lifecycle to reduce possible harm is another goal of green nanotechnology (Green Nanotechnology: Pioneering Sustainable Solutions in Materials Science - Advent Research Materials, 2025).

**DIFFERENCE BETWEEN NANOTECHNOLOGY AND GREEN NANOTECHNOLOGY**

The differences are given in table 1.

|  |  |  |
| --- | --- | --- |
| **Feature** | **Nanotechnology** | **Green Nanotechnology** |
| **Scope** | Broad area of nanoscale matter manipulation for a range of uses. | A particular subfield that prioritizes sustainability and reducing adverse effects. |
| **Primary Focus** | Engineering novel materials, devices, and systems at the nanoscale. | Environmentally responsible design, manufacture, and application of nanomaterials. |
| **Key Principles** | Taking advantage of special nanoscale characteristics. | Principles of green engineering and green chemistry. |
| **Goal** | Developments in a variety of fields, including materials, electronics, and medicine. | Sustainable development and minimizing risks to environment and human health. |
| **Synthesis Methods** | May use a variety of physical and chemical techniques; they are not always environmentally benign. | Focuses on environmentally friendly techniques that use non-toxic precursors and renewable resources. |
| **Taking Impact into Account** | Mostly on performance and usefulness. | Strong focus on the effects of the full lifespan, encompassing production, usage, and disposal. |
| **Application Focus** | Broad, encompassing topics that might not immediately relate to sustainability. | Frequently focuses on safer products and environmental solutions (clean energy, cleanup). |

Table 1: Nanotechnology and Green Nanotechnology.

The data in table 1 is a compilation of definitions and general knowledge of "Nanotechnology" and "Green Nanotechnology" from a variety of scientific publications, reviews, and instructional materials on the subjects. It is compiled from the body of information in the field rather than being simply taken from a single database.

**NANOTECHNOLOGY AND GREEN NANOTECHNOLOGY FOR SUSTAINABLE ENVIRONMENT REMEDIATION**

Environmental degradation, which includes contaminated water supplies, deteriorated soil, and polluted air, is becoming a global concern that necessitates creative and efficient repair techniques. While traditional approaches frequently fall short in terms of effectiveness, affordability, and long-term sustainability, nanotechnology has become a potent instrument that provides distinctive nanoscale solutions. But given the worries about nanotechnology's environmental impact, green nanotechnology concepts must be incorporated to guarantee genuinely sustainable and environmentally sound repair. Numerous nanoparticles with remarkable qualities that can be used to clean up the environment are made possible by nanotechnology. Superior adsorption capabilities for heavy metals, organic pollutants, and other contaminants are demonstrated by nanoparticles due to their high surface area to volume ratio and improved reactivity. According to Dileepkumar et al. (2020), nanocatalysts can help pollutants break down into less dangerous forms more effectively and with less energy. According to Schertzer et al. (2012), nano sensors make it possible to detect contaminants quickly and sensitively, which enables prompt intervention and focused cleanup efforts. Nanotechnology offers a flexible toolkit for addressing a variety of environmental contaminants, from using magnetic nanoparticles to remove oil spills to filtering tainted water using nanofiber membranes. However, there may be unforeseen environmental effects from the creation and use of nanomaterials. The very issues that nanotechnology seeks to address may be made worse by traditional approaches, which frequently use dangerous chemicals, require large energy inputs, and produce hazardous waste. This is where green nanotechnology becomes vital.

Green nanotechnology minimizes the environmental impact of producing and using nanomaterials by combining the concepts of sustainable engineering and green chemistry (Anastas & Warner, 2000b). According to Vance et al. (2015), this entails creating bio-based synthesis pathways with plant extracts or microbes, employing safe solvents, cutting down on manufacturing energy, and creating nanomaterials that are naturally biodegradable or recyclable. To achieve sustainable environmental remediation, nanotechnology and green nanotechnology must converge. Green synthesis techniques can be used to create extremely efficient nanomaterials, reducing the environmental impact of the repair procedure itself. In addition to providing an economical and effective solution, employing plant-derived nanoparticles for heavy metal removal also eliminates the need for dangerous chemicals that are frequently involved in the manufacture of traditional nanoparticles. The long-term environmental impact of remediation activities is also decreased by using recyclable or biodegradable nanoparticles for pollutant adsorption. Additionally, the principles of green nanotechnology direct the creation of safer and more ecologically friendly nanomaterial applications. According to Nel et al. (2006b), this entails creating nanomaterials with regulated mobility to avoid accidental environmental distribution and comprehending their possible ecotoxicity via thorough risk assessment studies.

The emphasis moves from merely cleaning up pollution to doing so in a way that minimizes additional environmental damage and fosters ecological health over the long run. The integration of green nanotechnology principles is where nanotechnology's true value lies, even though it has the potential to completely transform environmental remediation. We can effectively address environmental pollution at the nanoscale without endangering the health of our planet by putting a priority on sustainable synthesis, benign design, and responsible application. The combination of these two domains is not merely a technological development; it is also a moral necessity for realizing a cleaner and more sustainable future.

**POWERING A GREENER FUTURE: THE CONVERGENCE OF NANOTECHNOLOGY AND GREEN NANOTECHNOLOGY IN CLEAN ENERGY GENERATION**

A better global ecosystem and climate change mitigation depend heavily on the swift switch to sustainable and clean energy sources (WMO Community Supports Urgent Transition to Clean Energy, 2024). Innovative avenues to improve current clean energy technologies and create new, ecologically friendly energy generation techniques are provided by the convergence of nanotechnology and green nanotechnology. The efficiency and functionality of clean energy systems can be greatly enhanced by the toolset of nanoparticles with special qualities that nanotechnology offers. For example, in solar photovoltaics, nanomaterials such as perovskites and quantum dots are being investigated to improve energy conversion efficiency and light absorption, resulting in more potent and affordable solar cells (AZoQuantum, 2024).

In fuel cells, nanostructured catalysts are essential because they increase durability and reaction speeds while lowering the need for pricey precious metals (Kuterbekov et al., 2025). Additionally, nanotechnology plays a key role in developing energy storage solutions; nanomaterials allow batteries and supercapacitors to have longer lifespans, higher energy densities, and faster charging rates (Mauro, 2024). Green nanotechnology principles must be incorporated, though, to guarantee the sustainability of these nano-enabled energy systems (Narayanan & Bhaskar, 2024). For nanomaterials used in energy devices, this entails using environmentally friendly synthesis techniques, reducing waste production, and using more plentiful and less hazardous ingredients. As an example, scientists are looking at bio-templated synthesis of solar cell nanomaterials to lessen the production's environmental impact (Nuraje et al., 2012). A cradle-to-grave strategy is the main focus, taking into account the environmental effects of the energy technology across its whole existence. For a truly greener global ecosystem to be realized, the performance-enhancing potential of nanotechnology and the sustainability focus of green nanotechnology must work in concert. A cleaner and more sustainable energy future can be achieved by utilizing sustainably synthesized nanomaterials to develop high-efficiency solar cells, producing long-lasting and reasonably priced fuel cells with environmentally friendly catalysts, and enabling next-generation batteries with environmentally friendly components. The technological aspects of clean energy generation are improved by this convergence, which also guarantees that future generations will benefit from these developments by living on a healthier planet.

**NANOTECHNOLOGY-ENABLED ELECTRICITY GENERATION TECHNOLOGIES**

Modern civilization depends heavily on the production and upkeep of electricity, and in light of population increase, climate change, and the world's growing energy needs, the shift to clean, decentralized, and sustainable power production is of utmost importance (Samiul, 2025). By manipulating materials at the atomic and molecular level, nanotechnology presents new opportunities to greatly improve electricity generation technologies. Nanostructured materials have demonstrated revolutionary potential in fuel cells, solar cells, thermoelectric converters, and upcoming nanogenerator systems because of their huge surface area-to-volume ratio, programmable bandgaps, and quantum confinement effects. This section examines how nanotechnology can be incorporated into various platforms for producing electricity and evaluates the effects on scalability, sustainability, and efficiency.

* **Nanotechnology in Photovoltaic (Solar) Energy Conversion:**

The effectiveness and affordability of solar cells are two of the most well-known uses of nanotechnology in the production of power. The electron transport and light absorption capabilities of conventional silicon-based photovoltaics are limited. To address these issues, nanomaterials such as plasmonic nanoparticles, nanowires, quantum dots, and perovskite crystals have been employed. Semiconductor nanocrystals known as quantum dots (QDs) have size-tunable band gaps that enable them to absorb various solar radiation wavelengths. Because of their longer carrier diffusion lengths and improved exciton production, perovskite quantum dots (such CsPbBr₃) used in perovskite solar cells have attained efficiencies above 25% (Green et al., 2023).

In dye-sensitized solar cells (DSSCs), nanowire arrays composed of TiO2 and ZnO function as extremely effective electron transport layers, decreasing recombination and increasing photocurrent (Chen et al., 2021). Furthermore, localized surface plasmon resonance (LSPR) allows plasmonic nanoparticles like gold (Au) or silver (Ag) to concentrate sunlight at the nanoscale, improving light absorption and trapping (Zhang et al., 2020). A new generation of solar cells with improved power conversion efficiency (PCE), mechanical flexibility, reduced manufacturing costs, and wider applicability in off-grid, urban, and portable energy systems is the outcome of these advancements.

* **Piezoelectric and Triboelectric Nanogenerators (PENGs and TENGs):**

Devices that turn mechanical energy into electrical power, or nanogenerators, are a relatively new use of nanotechnology in the production of electricity. By using nanostructured piezoelectric materials like ZnO, BaTiO3, and PVDF, piezoelectric nanogenerators (PENGs) can produce electricity from pressure, vibrations, and body movements (Wang, 2022). These systems work well with wearables, biological implants, and self-powered sensors. Triboelectric nanogenerators (TENGs) also take advantage of the electrostatic induction and triboelectric action between two materials. A charge differential created by motion-induced interaction between nanostructured surfaces can be captured as electrical energy. According to Yang et al. (2020), TENGs can capture energy from wind, precipitation, walking, and even ocean waves.

Additionally, hybrid TENG-PENG systems have been created to optimize output across a wider frequency range. These nanogenerators promise broad use in environmental sensing, microelectromechanical systems (MEMS), and the Internet of Things (IoT) since they are not only effective but also affordable and scalable.

* **Nanostructured Thermoelectric Materials for Waste Heat Recovery:**

The Seebeck effect is used by thermoelectric generators (TEGs) to directly convert heat into electrical power. The thermoelectric figure of merit (ZT) determines how efficient these devices are; it increases with low heat conductivity and high electrical conductivity, two characteristics that may be precisely adjusted through nano-structuring. Lead telluride (PbTe), bismuth telluride (Bi2Te3), and skutterudites are examples of nanostructured materials that have been designed to decrease phonon transmission (heat conduction) while maintaining electron mobility (Zhao et al., 2019). The efficiency of energy conversion is greatly increased by this improvement.

Nanotechnology-enabled TEGs, which transform otherwise lost heat into useful power, are currently being investigated in wearable technologies, industrial heat recovery, and automobile exhaust systems. The estimated 60% of energy lost as heat in typical energy systems can be recovered in part by including nano-engineered thermoelectric (Snyder & Toberer, 2008).

* **Fuel Cells Enhanced by Nano Catalysts:**

Fuel cells are electrochemical devices that use the chemical reaction of hydrogen and oxygen to produce energy, with the sole byproduct being water. By enhancing catalyst performance, nanotechnology raises their affordability and efficiency. Nanoparticles based on platinum (Pt) are frequently employed in proton exchange membrane fuel cells (PEMFCs) as catalysts. Pt-Co or Pt-Ni alloy nanoparticles, which use less platinum and exhibit greater activity and longer durability, are recent developments (Ahmad et al., 2023). Nanostructured membranes and graphene-supported catalysts have also been developed to lower fuel crossover and improve ionic conductivity. Carbon nanotube (CNT)-embedded membranes and metal-organic frameworks (MOFs) offer yet another avenue for improving fuel cell longevity and performance.

These nano-enabled improvements are crucial for scaling up hydrogen-powered vehicles, stationary power systems, and microgrids, especially in regions transitioning away from fossil fuels.

* **Nanotechnology in Bioelectricity and Microbial Fuel Cells:**

The application of nanomaterials in microbial fuel cells (MFCs), which use bacteria to break down organic material and produce power, has been the subject of recent research. By facilitating better electron transport between microbial communities and electrodes, nanostructured anodes composed of graphene oxide, carbon nanofibers, or MnO2 nanoparticles increase power density and overall efficiency (Logan et al., 2019). Potential uses for these systems include wastewater treatment, where they can provide electricity and clean water. It is anticipated that the incorporation of nanotechnology will increase MFCs' cost-effectiveness and efficiency, bringing them closer to being used in decentralized energy systems.

* **Challenges and Opportunities for Scaling Nanotechnology in Electricity Generation:**

Commercialization of power generation enabled by nanotechnology is hampered by several issues, despite its potential:

**Material toxicity:** Certain nanoparticles, like lead and cadmium, are harmful to the environment and human health.

**Synthesis cost:** Production costs are raised by high-precision manufacturing techniques.

**Stability and degradation:** Extended exposure to heat, air, or sunshine can cause nanomaterials to deteriorate.

**Recyclability:** Recovering nanomaterials at the end of their useful lives is still a concern.

To get around this, research is concentrating more on green nanotechnology techniques, which use non-toxic, bio-based, and biodegradable precursors and make sure life cycle assessments (LCA) inform material creation. Low-energy chemical vapor deposition (CVD), microbiological processes, and plant extracts are examples of sustainable synthesis pathways that are gaining popularity (Narayanan & Bhaskar, 2024). Self-healing nanomaterials, intelligent nanoelectrodes, and flexible photovoltaic textiles are examples of potential future advancements that portend a new era of wearable and integrated electricity-generating technologies that promote low-carbon lifestyles.

Energy systems are becoming more compact, efficient, and ecologically friendly thanks to nanotechnology, which is transforming the production of electricity. Nano-enabled technologies are changing the face of renewable energy, from enhanced fuel cells and nanostructured thermo-electrics to high-efficiency solar cells and nanogenerators. Incorporating these developments into a framework for green nanotechnology guarantees that innovation is both potent and accountable. A key factor in attaining global energy sustainability will be the extensive use of electrical generation provided by nanotechnology as interdisciplinary research progresses.

**NANOTECHNOLOGY IN ENERGY STORAGE SYSTEMS: COMPLEMENTING ELECTRICITY GENERATION**

The production of electricity alone is no longer adequate as the global search for clean and sustainable energy accelerates (Samiul, 2023). Even the most cutting-edge generation technologies, including those made possible by nanotechnology, cannot ensure continuous, on-demand power without reliable and effective energy storage systems. For naturally sporadic renewable energy sources like solar and wind, this is especially important. Energy storage system design, development, and optimization are revolutionized by nanotechnology, which provides previously unheard-of benefits in terms of charge density, cycling stability, speed, safety, and downsizing. The field of energy storage has undergone a paradigm shift as a result of the combination of nanotechnology and electrochemical storage technologies, such as batteries, supercapacitors, and hybrid systems. This section addresses the present and future use of nanomaterials in sophisticated energy storage systems as well as how they might be integrated with renewable energy-producing technology.

**1. Nanostructured Electrodes in Advanced Battery Systems:**

Traditional batteries, especially lithium-ion batteries (LIBs), have transformed portable gadgets and are now necessary for grid storage and electric cars. However, the constraints of bulk electrode materials frequently limit their performance. The construction of nanostructured electrodes, which provide increased surface area, shortened ion diffusion routes, and higher electrical conductivity, has been made possible by nanotechnology.

* **Graphene and Carbon Nanotubes in Lithium-Ion Batteries:** Carbon nanotubes (CNTs), which are cylindrical carbon structures with remarkable electrical and mechanical properties, and graphene, a sheet of carbon atoms that is one atom thick, have become the most popular electrode materials for lithium-ion batteries. Anodes based on graphene have better flexibility, thermal conductivity, and specific capacity. Faster electron transport and the avoidance of lithium dendrite formation—a major obstacle to battery safety—are made possible by its two-dimensional structure (Xie et al., 2022). The development of flexible and high-capacity electrodes is made possible by the great tensile strength, electrical conductivity, and porosity of both single-walled and multi-walled carbon nanotubes. Additionally, CNTs can be used as scaffolds to embed active materials like silicon, tin oxide, or transition metal oxides, greatly improving their stability and electrochemical performance across several charge-discharge cycles (Zhang et al., 2021).
* **Nanotechnology in Sodium-Ion and Solid-State Batteries:** Particularly for large-scale grid applications, sodium-ion batteries (SIBs) are becoming more and more popular as a less expensive and environmentally friendly substitute for LIBs. Improved capacity retention and rate capability are provided by nanostructured cathode and anode materials, such as carbon-coated NaTi₂(PO4)3 nanoparticles and NaV2(PO4)3 nanocrystals. The volume expansion problems during ion intercalation and deintercalation, which frequently reduce SIB lifetime, are lessened by nanotechnology. Solid electrolytes with strong ionic conductivity and thermal stability are engineered using nanomaterials in solid-state batteries (SSBs). For example, at normal temperature, nano-porous garnet-type Li7La3Zr2O12 (LLZO) ceramics have superior lithium-ion conduction. Furthermore, interfacial resistance- a key bottleneck in modern SSB technology- is greatly decreased by nanostructured interfaces between electrodes and electrolytes (Zhao et al., 2023).

**2. Nano-Supercapacitors for Fast Charge-Discharge Cycles:**

Rapid charge-discharge rates, extended cycle life, and high-power density-albeit at a lower energy density than batteries, are characteristics of supercapacitors, often referred to as electrochemical capacitors, which are energy storage devices. Nanotechnology uses ultrafine electrode designs and pseudocapacitive materials to create nano-supercapacitors with improved performance.

* **Electrode Design Using Nanostructured Materials:** Modern supercapacitor electrodes are based on nanostructured materials, including conducting polymers, metal oxides (such as MnO2 and RuO2), graphene nanosheets, and activated carbon nanofibers. More charge storage and electrolyte ion accessibility are made possible by their large surface area. For instance, hybrid electrodes that combine graphene or CNTs with MnO2 nanoparticles improve electrical conductivity and pseudo-capacitance. Such nanomaterials have high specific capacitances and exceptional cycling stability (>100,000 cycles) in both symmetric and asymmetric topologies, which makes them perfect for use in grid frequency regulation, portable electronics, and regenerative braking systems (Wang et al., 2021).
* **Micro-Supercapacitors and Flexible Devices:** Beyond large-scale uses, nanotechnology has made it possible to develop flexible, tiny, and wearable micro-supercapacitors (MSCs) that can be integrated into biomedical or wearable devices. Because of their electrical and mechanical qualities, 3D graphene, carbon aerogels, and MXene nanosheets are frequently used. The importance of nanotechnology in next-generation energy ecosystems is further expanded by these nanoscale devices, which provide energy buffering and autonomous power supply in self-powered systems.

**3. Integration with Intermittent Renewable Energy Sources:**

The discrepancy between energy production and demand is one of the most urgent issues facing renewable energy. Wind and solar energy are, by their very nature, variable and sporadic (Islam, 2025; Samiul, 2025). Energy systems become more adaptable, robust, and able to provide steady power by directly combining nano-enhanced storage systems with generating sources. Batteries with nanostructured anodes and cathodes aid in solar systems by storing extra energy during the day and releasing it at night or when there is cloud cover. Supercapacitors with graphene or carbon nanotube electrodes can swiftly capture and release energy during gust oscillations in wind farms, assisting in the smoothing out of grid input. Compact and effective storage solutions provided by nanotechnology are extremely beneficial for microgrids and off-grid systems, especially in rural or climate-vulnerable areas. Without relying on fossil fuels, these decentralized systems generate clean electricity, promoting climate resilience, sustainability, and energy availability.

**4. Future Horizons: 3D- Printed Nanomaterial-Based Storage Devices:**

The development of next-generation, architectural energy storage devices is being facilitated by the combination of nanotechnology and 3D printing. Researchers are employing nanocomposite inks made of metal-organic frameworks, graphene, or carbon nanotubes to create 3D-printed batteries and supercapacitors. These technological advancements enable:

* Personalized shapes that minimize resistance and maximize surface area.
* incorporation into structural materials (such as drone wings and wearable electronics).
* On-demand manufacturing for military, emergency, or distant applications.

The energy and power densities of traditional lithium-ion coin cells can be matched or surpassed by 3D-printed micro batteries that use graphene oxide and silver nanowires, according to recent research (Sun et al., 2022). Energy systems engineering may undergo a revolution as a result of the possibility of fabricating energy storage devices and generators in a single integrated printing process as the technology advances.

Energy storage is being redefined by nanotechnology, which is producing materials and designs that are safer, lighter, faster, and more flexible to meet the changing needs of contemporary power systems. Impacts range from stabilizing renewable energy outputs to developing 3D-printed storage modules, and from enhancing lithium-ion battery performance to enabling ultra-fast nano-supercapacitors. The use of nanotechnology in energy storage will become increasingly important as energy systems move toward decentralization and decarbonization. Its incorporation into power generation systems guarantees not only clean production but also safe, intelligent, and sustainable energy delivery- a vital requirement for creating a more environmentally friendly global ecology.

**HYBRID NANOTECHNOLOGY- ENABLED SYSTEMS FOR CONTINUOUS ELECTRICITY SUPPLY**

One major technical difficulty brought to light by the global shift to renewable and decentralized electrical systems is how to guarantee a steady, dependable, and uninterrupted supply of power from naturally intermittent sources like wind and solar. As a result, hybrid energy systems that integrate generating and storage methods made possible by nanotechnology are becoming more and more popular. Researchers and engineers are creating self-sustaining, intelligent systems that can provide continuous electricity in a variety of environmental and usage contexts by utilizing the complementary strengths of various nanomaterial-based technologies, such as solar photovoltaics, piezoelectric/triboelectric nanogenerators (PENGs/TENGs), supercapacitors, and fuel cells. Each energy module's efficiency is increased by nanotechnology, which also makes it possible for them to be seamlessly integrated into multipurpose hybrid systems. These setups hold great promise for wearable electronics, remote sensors, disaster-resilient microgrids, self-powered IoT devices, and smart city infrastructure.

**1. Hybrid Systems: Combining Complementary Nanogenerators:**

Integrating many nanotechnology-enabled devices into a single hybrid system provides a solution to improve dependability and get around intermittency. Combining solar cells with piezoelectric or triboelectric nanogenerators (TENGs or PENGs) is one such tactic.

* **Solar Cell + TENG/PENG Hybrid Systems:** Solar photovoltaics produce a lot of energy while illuminated, but when there is no sunlight around, they function much worse. On the other side, TENGs and PENGs are great supplemental sources during overcast or nocturnal conditions since they capture energy from mechanical stimuli like vibrations, wind, rain, or human motion. For instance, scientists have created hybrid flexible panels that combine ZnO-based TENG layers with perovskite solar cells, allowing for the simultaneous harvesting of mechanical and solar energy (Fan et al., 2020). These gadgets are perfect for agricultural sensors and environmental monitoring stations since they can continually power small-scale electronics in outdoor settings.
* **Fuel Cell + Supercapacitor Integration:** Fuel cells and nanostructured supercapacitors are combined in another effective hybrid design. Supercapacitors offer quick charge-discharge cycles and power bursts for peak demands, while fuel cells have a high energy density and may operate for extended periods. This synergy is made possible by nanotechnology:

a) Using Pt-based nanoparticles to enhance fuel cell catalysts for quicker reaction kinetics.

b) Using metal oxides, graphene, and carbon nanotubes (CNTs) to improve supercapacitor electrodes.

c) Establishing shared hybrid interfaces that use supercapacitors to temporarily store excess fuel cell energy.

These systems are being investigated for use in microgrids, electric vehicles, and uninterruptible power supply (UPS) systems where rapid reaction and consistent power delivery are critical.

**2. Self-Powered IoT Devices and Wearables:**

The Internet of Things (IoT) needs dependable, maintenance-free power for its billions of smart gadgets. Self-powered Internet of Things devices that integrate different nanoscale energy collecting and storage components into incredibly small structures are now feasible thanks to nanotechnology.

* **TENG/PENG-Integrated IoT Modules:** IoT sensors can capture energy from mechanical activity (such as footsteps, wind, or engine vibrations) and ambient light by combining TENGs or PENGs with thin-film solar cells. These modules are hybrids:

a) Function without batteries in distant or mobile situations.

b) Encourage wearable health tracking, agriculture, logistics, and structural health monitoring.

c) Because of their lightweight and flexible design, they operate with little influence on the environment.

One significant advancement in sustainable biomedical electronics is the ability of a wearable gadget that uses a PENG solar cell combination to constantly monitor mobility, temperature, and heart rate without requiring battery replacement (Wang et al., 2022).

* **Integration with Flexible and Transparent Nanomaterials:** Stretchable, transparent hybrid energy systems that are perfect for wearable electronics can be developed thanks to the flexibility of nanomaterials like graphene, MXenes, and carbon nanofibers. By acting as conductors, electrodes, and active sensing layers all at once, these materials eliminate the need for large circuitry.

**3. Applications in Smart Grids and Decentralized Power Networks:**

Hybrid nanotechnology-enabled systems also play a growing role in the evolution of **smart grids-**intelligent, decentralized electricity systems that dynamically manage supply and demand.

* **Nanotechnology-Enhanced Smart Grid Components:** The development of smart grids is aided by nanotechnology via:

a) Enhancing modular batteries' and supercapacitors' energy density and charge-discharge efficiency.

b) Enabling temperature, voltage, and frequency monitoring at dispersed nodes using real-time nano-sensor networks.

c) Powering self-healing circuits using nanomaterials that remember shapes.

Nanomaterial-enabled solar–supercapacitor hybrid microgrids are becoming more and more popular for off-grid electrification in rural or disaster-prone locations. These systems provide a constant supply by storing excess solar energy during the day and delivering it at night via battery banks improved with nanotechnology.

**4. Nanotech-Based AI Energy Management Systems:**

As hybrid systems become more complex, efficient energy management becomes essential. Artificial Intelligence (AI), in combination with nanotechnology, is now being employed to optimize power generation, conversion, and usage in real time.

* **AI Algorithms for Power Optimization:** AI is useful for:

a) Estimate the power output of nanogenerators by taking into account environmental factors including vibration, wind, and sunlight.

b) Depending on availability, dynamically switch between various energy modules (such as solar vs. TENG).

c) Avoid overcharging and gradually maintain the health of the nanobattery.

Nanosensors and embedded nanoprocessors that can gather and analyze operational data at the micro- or nanoscale make these functionalities possible.

* **Digital Twins of Nano-Hybrid Power Systems:** Digital twins, or virtual representations of actual nano-enabled energy systems, are used in more complex solutions. These twins provide energy forecasting, defect detection, and predictive maintenance by simulating real-world performance. This method is especially helpful for managing transportation grids, emergency power systems, and urban smart energy networks where downtime is crucial.

Systems made possible by hybrid nanotechnology are a vital step forward in the development of robust, sustainable, and independent electrical networks. With the help of real-time AI management systems and the clever fusion of energy sources like as solar cells, TENGs, fuel cells, and supercapacitors, these hybrid platforms guarantee reliable energy delivery even in harsh or fluctuating environmental circumstances.

The future of energy depends on the smooth integration of nanotechnology into all aspects of generation, storage, and intelligent control, from stable smart grids and remote microgrids to powering self-sufficient Internet of Things devices and wearable health monitors. In order to achieve ecological harmony and global energy equity, hybrid nano-enabled systems will be crucial as materials and computational technology advance.

**EMERGING WATER-ACTIVATED NANOTECHNOLOGIES FOR ELECTRICITY GENERATION**

There is a lot of unrealized potential for producing clean power from water in all of its forms and motions, including flow, salinity gradients, evaporation, and humidity. A new class of technologies known as hydro voltaic and osmotic power systems has emerged as a result of recent developments in nanotechnology that have made it possible to develop creative ways to capture energy from interactions with water. These new technologies use the nanoscale characteristics of materials, including ionic channels, graphene oxide, and nano-porous membranes, to transform water movement or contact into electrical power that may be used. Nanotechnology-based water-activated energy systems are small, effective, and appropriate for off-grid or decentralized deployments, in contrast to conventional hydroelectric systems that rely on extensive infrastructure. They can be used in disaster-prone locations, isolated rural areas, and coastal zones where a reliable electrical supply is scarce or interrupted.

**1. Hydro-Voltaic Generators Using Graphene Oxide Membranes:**

The direct conversion of water contact (flow, wetness, evaporation, etc.) with nanomaterials into electrical power is known as hydro-voltaic energy harvesting. Graphene oxide (GO), a two-dimensional carbon-based material with hydrophilic qualities and functional groups including oxygen, is one of the most promising materials for such systems. Electric double layers (EDLs) are created along the nanosheets as a result of charge redistribution when water passes through GO films or membranes. Ionic migration and electron transfer brought on by the constant motion of water molecules produce a detectable voltage or current (Yin et al., 2021). This system may be activated by:

* Water drops gliding across surfaces coated with GO.
* Variations in humidity throughout GO nanofilms.
* Capillary flow caused by evaporation in nano-porous GO structures.

Hydro-voltaic generators using GO have demonstrated the ability to generate electricity in ambient environments without external voltage or moving parts. These systems are:

* **Scalable.**
* **Low-cost.**
* **Environmentally friendly.**

Their potential use includes **environmental sensors, wearable electronics**, and **emergency micro-power sources** in off-grid regions.

**2. Osmotic Power Generation Using Nano-porous Membranes (Blue Energy):**

The natural mixing of fresh and saltwater, especially around river mouths where they converge, produces osmotic energy, often known as "blue energy." Ion’s flow across a semi-permeable membrane to release energy, generating an electrochemical potential difference that can be converted into electrical power. By creating nano-porous membranes with regulated pore size, surface charge, and ion selectivity, nanotechnology greatly improves this process. Among the noteworthy materials are:

* Membranes made of carbon nanotubes.
* MoS2 nanosheets and MXenes.
* Nanopores in graphene.
* Nanofibers of cellulose with functional coatings.

These membranes enable:

* **High ion flux.**
* **Selective transport of cations or anions.**
* **Minimal energy loss.**

By moving sodium and chloride ions from saltwater through the nanopores to freshwater, reverse electrodialysis (RED) or pressure-retarded osmosis (PRO) creates a voltage across the membrane. Osmotic power is a feasible option for floating platforms, desalination facilities, and coastal power plants, as recent research has shown power densities of up to 5 W/m2 (Hou et al., 2020).

**3. Water-Evaporation-Driven Nanogenerators:**

Using water evaporation, a common and ongoing natural process, to generate energy is another amazing advancement in water-activated nanogenerators. Researchers have created gadgets that use asymmetric nanostructures to transform movement caused by moisture into electrical power. Devices composed of bacterial cellulose sheets or asymmetric polyelectrolyte membranes coated with nano-porous carbon, for instance, use the differential in water content between the top and bottom surfaces to create electrical current and ion movement. These technologies have potential in:

* **Low-power water purification systems.**
* **Remote environmental monitoring.**
* **Self-sustaining data collection buoys in lakes and oceans.**

They require **no external energy input**, are **biodegradable**, and can function even in humid air or with wastewater.

**4. Practical Applications in Coastal, Remote, and Disaster-Prone Areas:**

Water-activated nanotechnologies are particularly well-suited to regions where traditional energy infrastructure is:

* Inaccessible (e.g., mountainous, remote, or island communities).
* Unreliable due to climatic or political instability.
* Vulnerable to natural disasters (e.g., floods, tsunamis, cyclones).

1. **Coastal Power Solutions:** Blue energy systems based on nano-porous membranes can use the constant mixing of fresh and saltwater in coastal and estuarine regions to generate electricity.

* Telecom apparatus.
* Aids for maritime navigation.
* Desalination plants for seawater.

1. **Remote Off-Grid Communities:** For rural populations, GO-based hydro-voltaic panels or evaporation nanogenerators can provide decentralized power for:

* LED lighting.
* Charging mobile phones.
* Pumping groundwater.

1. **Emergency and Disaster Response:** Compact hydro-voltaic and osmotic power units can be used in disaster-prone areas where grid power is frequently lost, as:

* Backup energy for vital medical equipment.
* Weather stations that operate on their own.
* Tools for emergency communication.

Nanomaterials' modular design, low weight, and lack of toxicity make them perfect for quick deployment and integration with portable infrastructure.

A new and sustainable frontier in localized electricity generation is represented by emerging water-activated nanotechnologies. These systems create new opportunities for the production of green energy in environments with limited resources by utilizing natural processes like water flow, evaporation, and salinity gradients, and fusing them with cutting-edge nanomaterials like graphene oxide and nano-porous membranes. The implementation of hydro-voltaic and osmotic nanogenerators could provide robust, affordable, and ecologically friendly solutions- empowering communities while lowering the global carbon footprint- as climate change intensifies the frequency of disasters and puts stress on centralized power networks. Enhancing efficiency, scalability, and integration with current technology will require ongoing interdisciplinary study.

**NANOMATERIAL APPLICATIONS IN GEOTHERMAL AND THERMOPHOTOVOLTAIC ELECTRICITY GENERATION**

Thermal energy is a huge and underappreciated source of sustainable power, particularly when it comes to high-temperature radiation and geothermal heat. Historically, large-scale mechanical systems like steam turbines have been used to convert heat into electricity. Nonetheless, the development of nanotechnology is making it possible to employ nanomaterials in direct, compact, and effective heat-to-electricity conversion systems, particularly in thermophotovoltaic (TPV) and geothermal applications. This section examines how various thermal energy technologies are being transformed by nanofilms, nano-coatings, and nano-catalysts, which enable them to operate more efficiently, endure harsh environments, and blend in perfectly with contemporary energy infrastructures.

**1. Nanotechnology in Thermophotovoltaic (TPV) Electricity Generation:**

Thermophotovoltaic systems use photovoltaic (PV) cells to turn radiant heat from a hot source into electrical power. TPV systems employ infrared radiation from a thermal emitter heated to temperatures between 1000°C and 2000°C, as opposed to solar PV, which uses sunshine. Innovations are made possible by nanotechnology at each crucial TPV system junction:

1. **Thermophotovoltaic Nanofilms:** Both the emitter and the PV receiver are engineered using nanofilms and metamaterials:

* It is possible to adjust selective emitters, like graphene-integrated nanofilms or tungsten-based photonic crystals, to exclusively emit wavelengths that correspond to the TPV cell's bandgap.
* By trapping heat photons through plasmonic and photonic processes, reducing reflection, and increasing efficiency, nano-patterned PV cells enhance light absorption.

In near-infrared TPV systems, for example, quantum well infrared photodetectors (QWIPs) and nanostructured InGaAsSb cells have shown enhanced power conversion, with efficiencies above 30% (Zhang et al., 2022).

**2. Geothermal Energy Harvesting Using Nanomaterials:**

By using geothermal reservoirs, hot springs, or even enhanced geothermal systems (EGS), geothermal energy may access the heat that exists within the Earth. Geothermal systems are improved by nanotechnology mainly in two ways:

1. **Nanofluids for Enhanced Heat Transfer:** To increase heat transfer rates during drilling, fluid circulation, or energy extraction, geothermal systems employ nanofluids, which are base fluids (water, oil, or glycol) enhanced with high-conductivity nanoparticles such as AlO3, CuO, or carbon nanotubes. This makes it possible for:

* Increased heat conductivity.
* Less energy loss while transferring.
* Improved geothermal heat exchanger performance.

1. **Nano-coatings for Geothermal Equipment:** Extreme thermal and chemical conditions, such as high temperatures, mineral scaling, and corrosion, are experienced by geothermal plants. High-performance nano-coatings derived from silicon carbide nanoparticles, alumina, or ceramic-metal composites (cermets) provide:

* Resistance to heat up to 1200°C.
* Protection against erosion and corrosion.
* Increased durability of turbines, pumps, and heat exchangers.

According to recent studies, scaling deposition and surface degradation can be decreased by plasma-sprayed nanostructured coatings, which is particularly important in high-salinity geothermal regions (Kumar et al., 2021).

**3. Nano-Catalysts for Thermal Stability and Energy Conversion:**

Maintaining thermal stability and reaction efficiency is crucial in both geothermal and TPV systems, particularly when exposed to high temperatures for extended periods of time. Nano-catalysts are essential for:

* Enhancing heat exchanger materials' resistance to heat.
* Accelerating chemical reactions in geothermal fluids (geothermal steam can be used to produce hydrogen, for example).
* Allowing TPV reactors to convert heat thermochemically.

For example, the capacity of noble metal nanoparticle catalysts, such as Pt, Pd, and Ru, supported on ceramic nanostructures to maintain high-temperature catalytic processes without sintering or deactivation is being investigated. Nano-engineered heat-resistant barriers and interfacial nanolayers are employed in TPV systems to prolong device lifetimes and stop thermal deterioration of materials.

**4. Future Integration and Combined Technologies:**

One intriguing approach to dispatchable and continuous power generation is the incorporation of nanomaterials into geothermal–TPV hybrid systems. These systems are capable of:

* Directly power TPV systems using geothermal heat.
* Use phase change materials (PCMs) augmented with nanomaterials to store excess heat.
* Use intelligent coatings that can repair themselves when exposed to heat stress.

Furthermore, AI-integrated nanomaterial sensors may be used in the future to track thermal degradation in real time, enhancing dependability and facilitating predictive repair of vital infrastructure.

**5. Environmental and Strategic Applications:**

Thermal energy systems boosted by nanotechnology are particularly helpful in:

* Nations with abundant geothermal resources (such as Iceland, Kenya, and Indonesia).
* Heat recovery from industrial waste.
* Subterranean or remote data centers looking for environmentally friendly electricity and cooling.
* Space missions, where nanomaterial-based TPV systems can capture solar thermal radiation or radioisotope decay energy.

Modular geothermal TPV systems with nanomaterials can power microgrids, decentralized water purification units, or refrigerators in low- and middle-income nations, guaranteeing resilience and sustainability.

High-efficiency, heat-based energy conversion is reaching new heights thanks to the use of nanomaterials in geothermal and thermophotovoltaic power generation. These systems can survive extreme heat conditions, maximize energy capture, and provide dependable electricity in both centralized and decentralized settings by utilizing nanofilms, high-temperature nano-coatings, and nano-catalysts. Nanotechnology provides an essential toolkit for capturing Earth's natural heat and radiant energy with previously unheard-of accuracy and durability as the world works to move away from fossil fuels. These technologies will probably be combined with AI and smart systems in future developments to optimize performance dynamically and sustainably over the long run.

**ARTIFICIAL INTELLIGENCE-DRIVEN OPTIMIZATION OF NANO-ENABLED POWER SYSTEMS**

Nanotechnology has brought previously unheard-of levels of efficiency, compactness, and adaptability to contemporary electricity generation and storage technologies. However, sophisticated methods for optimization, monitoring, and predictive control are necessary due to the intricacy and interconnectedness of these nano-enabled systems, which include smart nanomaterials, decentralized energy modules, and dynamic environmental interactions. Here's where artificial intelligence (AI) can make a big difference (Islam, 2025). Researchers and engineers are allowing self-learning, self-healing, and self-optimizing power systems that anticipate performance, adjust to changing conditions, and proactively handle failures by fusing AI with nanotechnology. The future of intelligent, sustainable energy networks- also known as AI-augmented nano-power systems or nano-smart grids- is being shaped by this new convergence.

**1. AI Algorithms for Performance Prediction and Nanomaterial Design:**

The creation and optimization of nanoparticles themselves is one of the most significant uses of AI in nano-enabled power systems. Conventional experimental approaches to material discovery are costly and time-consuming. AI speeds up this procedure by:

* Using machine learning (ML) models to forecast the correlations between structure and properties.
* Maximizing the parameters of nanomaterial synthesis, such as temperature, doping concentrations, and shape.
* Evaluating potential materials for catalytic, photovoltaic, or energy storage capabilities.

For instance, deep learning models have been used to improve the architecture of quantum dot solar cells for optimal efficiency and to forecast the electrical conductivity and charge mobility of graphene-based composites (Butler et al., 2018). Similarly, thermoelectric nanostructures with high figure-of-merit (ZT) values are being designed using reinforcement learning and genetic algorithms.

AI techniques like Bayesian optimization, support vector regression (SVR), and neural networks are useful in real-time energy systems because they:

* Estimate the amount of energy that solar or wind-powered nanogenerators will produce.
* Model the thermal behavior of battery systems that contain nanoparticles.
* Adjust control parameters in response to environmental feedback to increase operating efficiency.

**2. Nano-Sensor-Integrated Smart Grids for Real-Time Feedback and Fault Detection:**

Nano-sensors, ultra-sensitive, miniature sensors that can detect electrical, thermal, chemical, and mechanical factors at high resolution- have been made possible by advanced nanomaterials. These nano-sensors serve as the grid's "nervous system" when integrated with nano-enabled power systems, allowing for adaptive decision-making, anomaly detection, and real-time data collection.

1. **Applications in Fault Detection and Predictive Maintenance:** Data analytics powered by AI and fed by nano-sensor networks can:

* Identify overheating or short circuits in supercapacitors or batteries with nanotechnology.
* Determine which solar modules' performance declines are caused by material deterioration.
* In TENGs, PENGs, or nano-structured fuel cells, keep an eye on mechanical stress and fatigue.

A nano-sensor array placed inside a nanostructured lithium-ion battery pack, for example, is capable of measuring charge-discharge rates, temperature gradients, and voltage differentials. By predicting battery longevity, failure rates, and ideal usage cycles, AI models trained on this data can increase system safety and dependability.

1. **Real-Time Optimization in Distributed Nano-Microgrids:** AI-based control systems use data from nano-sensors to dynamically distribute power from solar cells, supercapacitors, and nanogenerators in decentralized or hybrid grids. During power shortages, methods like recurrent neural networks (RNNs), decision trees, and fuzzy logic control are employed to prioritize vital loads, minimize losses, and maximize energy flow.

**3. Digital Twins of Nano-Enabled Power Infrastructure:**

With the use of simulation models and real-time data, a digital twin is a virtual representation of a physical system that mimics its behavior. Digital twins can be made for the following purposes in the context of nano-enabled power systems:

* **Nano-enhanced solar farms.**
* **Battery storage systems.**
* **Hybrid nanogenerator platforms.**
* **Microgrids integrating AI and IoT.**

These twins incorporate:

* **High-fidelity material models** derived from nano-characterization.
* **Live input from nano-sensors.**
* **AI simulations of performance under varying conditions.**

1. **Benefits of Digital Twins in Energy Management:**

* **Predictive diagnostics:** Diagnose component failures in advance with predictive diagnostics.
* **Virtual commissioning:** Before deployment, test the system's performance through virtual commissioning.
* **Scenario planning:** Create scenarios that model how a system would react to changes in the environment, like a grid outage.
* **Optimization:** Real-time assessment of energy-saving tactics.

The digital twin, for instance, can forecast efficiency declines brought on by thermal stress in a TPV power plant with nanocoated emitters and suggest preventive coating modifications or load balancing to prevent losses.

1. **Integration with Edge and Cloud Computing:** Digital twins use edge devices (local microprocessors) or the cloud to handle the massive data streams from simulation models and nano-sensors. The twins' decision-making is coordinated by AI agents, allowing:

* Autonomous energy delivery.
* Forecasting load at the system level.
* Reconfiguration that adapts to errors.

This method works especially well in remote or disaster-prone locations where real-time performance monitoring is essential but physical access to infrastructure is restricted.

The intelligent core of energy systems enabled by nanotechnology is quickly evolving into artificial intelligence. AI makes real-time optimization, fault detection, material innovation, and autonomous system control possible through sophisticated algorithms, digital twin modeling, and nano-sensor integration (Islam, 2025). The combination of AI and nanotechnology will be essential to creating intelligent, flexible, and highly efficient power networks as the global energy landscape moves toward decentralization, sustainability, and resilience. In addition to improving energy systems' longevity and performance, this collaboration makes it possible to manage power generation, storage, and distribution in a proactive, data-driven manner despite the complexity of technology and the environment.

**LIFE CYCLE SUSTAINABILITY AND RISK ASSESSMENT OF NANO-ENABLED ELECTRICITY GENERATION TECHNOLOGIES**

Even while technologies for power production enabled by nanotechnology show promise in terms of performance, compactness, and adaptability, it is crucial to evaluate their long-term environmental impact and overall sustainability. A truly green energy solution must be assessed throughout its whole life cycle, from the extraction and manufacturing of raw materials to use, disposal, or recycling, in addition to its operational efficiency. The life cycle sustainability and risk assessment (LCSRA) of nano-enabled power systems is presented in this part. It includes a comparative carbon footprint, cradle-to-grave analysis, and important green nanotechnology criteria, including biodegradability, toxicity, and recyclability. It emphasizes how crucial it is to do a comprehensive assessment to make sure that these cutting-edge technologies complement the more general objectives of environmental conservation, the circular economy, and public health safety.

**1. Cradle-to-Grave Life Cycle Assessment (LCA) of Nano-power Technologies:**

A standardized methodology (ISO 14040/44) called life cycle assessment (LCA) is used to measure the environmental effects of a system, process, or product at every stage of its existence:

* **Cradle-to-Gate**: From raw material extraction to product manufacture.
* **Gate-to-Grave:** From the implementation of the system to the latter stages of care.
* **Cradle-to-Grave:** thorough examination from point of origin to point of disposal.

The LCA procedure in nano-enabled energy systems needs to take into consideration:

* **Source of material:** Nanoparticle mining and production (e.g., graphene, carbon nanotubes, quantum dots).
* **Energy inputs:** Energy inputs include chemical reagents or high temperatures employed in the creation of nanomaterials.
* **Emissions from manufacturing:** waste disposal, byproducts, and solvent use.
* **Impacts of the usage phase:** Energy production versus deterioration or leaking.
* **End-of-life considerations:** disposing of nano-embedded gadgets in a landfill, recycling, or burning.

According to a number of studies, although nano-solar cells and nanogenerators have lower operating emissions, unless they are tailored for green synthesis, their fabrication phase may have higher energy intensity and toxicity than conventional technologies (Sinha et al., 2018).

**2. Carbon Footprint Comparison with Conventional Energy Technologies:**

Carbon footprint analysis, a part of life cycle assessment (LCA), is necessary to ascertain whether nano-enabled power systems lessen environmental impact. This involves measuring:

* Total emissions of CO2 equivalent per kWh generated.
* **Energy Payback Time (EPBT):** The amount of time needed to produce the energy utilized during production is known as the Energy Payback Time (EPBT).
* **Energy Return on Investment (EROI):** The ratio of energy production to input is known as the energy return on investment, or EROI.

1. **Positive Outcomes:**

* Compared to crystalline silicon cells, nanostructured solar cells (such as perovskite, QD, and DSSCs) have lower EPBTs (less than a year) and lower CO₂ emissions while in operation.
* PENGs and triboelectric nanogenerators (TENGs) produce no emissions when in operation because they don't require fuel.

1. **Concerns:**

* Rare-earth metals, hazardous solvents, or high-energy inputs (such as those used in CVD and ALD procedures) are frequently used in the production of nanomaterials.
* Because metallic nanoparticles and non-biodegradable polymer composites might linger in landfills or seep into waterways, disposing of nano-enabled gadgets presents difficulties.

Therefore, even though operating footprints are minimal, if eco-friendly synthesis and closed-loop recycling technologies are not used, the benefits may be outweighed by the manufacturing and disposal stages.

**3. Green Nanotechnology Metrics: Toxicity, Recyclability, Biodegradability:**

Green nanotechnology designs safe, recyclable, and renewable nanomaterials in an effort to reduce risks and increase sustainability. The following metrics must be considered while evaluating nano-enabled energy systems:

1. **Toxicity:**

* Certain nanomaterials' tiny size, strong reactivity, and persistence in biological and ecological systems give rise to nanotoxicity.
* If released untreated, metal oxide nanoparticles (such as ZnO and TiO2) may harm aquatic species' DNA or induce oxidative stress.
* Commonly used in solar cells, cadmium-based quantum dots (CdSe, CdTe) are extremely poisonous and pose long-term environmental risks.

1. **Strategies for Toxicity Mitigation:**

* Use non-toxic substitutes, such as copper indium gallium selenide (CIGS) and carbon dots.
* Use encapsulation or surface passivation methods to stop leaching.

1. **Recyclability:** It is challenging to recover nanomaterials from wasted devices because

* Low concentrations of the substance.
* Combined embedding.
* Absence of a standardized infrastructure for recycling.

1. **Recyclability Approaches:**

* Design for disassembly (DfD).
* Employ magnetic nanoparticles for easier separation.
* Use soluble binders in nano-electrode fabrication to facilitate extraction.

1. **Biodegradability:** TheBiodegradation of nanoparticles is rare. Nonetheless, encouraging studies are being conducted on:

* Nanocomposites based on cellulose.
* Nanoparticles linked to chitosan.
* Conductive polymers inspired by biotechnology.

These materials are perfect for biomedical wearables, temporary gadgets, and ecologically sensitive applications like tracking wildlife or agriculture.

**4. Risk Assessment and Ethical Considerations:**

When implementing nano-enabled energy systems, sociological and ethical issues must be taken into consideration in addition to environmental effects:

* Hazards to workers' exposure while working during production.
* Data privacy in smart grids driven by nano-sensors.
* Environmental fairness in the location of production or disposal plants.

A thorough framework for risk governance ought to comprise:

* Concept of precaution for unknown toxicity.
* Participation of stakeholders in the design and implementation process.
* Harmonizing regulations at the national and international levels (e.g., ISO/TC 229, REACH).

The development and implementation of nano-enabled electricity generation systems depend heavily on life cycle sustainability and risk assessment. These systems have significant advantages in terms of operational emissions and energy efficiency, but their toxicity, manufacturing, and end-of-life effects need to be carefully controlled. Researchers and policymakers can make sure that nanotechnology contributes to a more sustainable, moral, and ecologically balanced global ecosystem in addition to making the world more electrified by implementing green chemistry principles, creating recyclable architectures, and performing cradle-to-grave life cycle assessments.

**CREATING A GREENER FUTURE: THE ROLE OF NANOTECHNOLOGY AND GREEN NANOTECHNOLOGY AS GLOBAL SUSTAINABILITY ACCELERATORS**

The realization of a more environmentally friendly global ecosystem depends on our capacity to resolve urgent environmental issues and make the shift to sustainable practices in every industry. To help us achieve this, nanotechnology provides a strong and adaptable toolkit, especially when applied following the principles of green nanotechnology. Its influence penetrates many areas essential to ecological well-being, going beyond environmental cleanup and the production of renewable energy. A noteworthy contribution is the creation of sustainable materials. By enabling the production of biodegradable, robust, and lightweight nanomaterials, green nanotechnology lessens waste production and dependency on conventional materials that need a lot of resources. By being used in manufacturing, building, and packaging, these cutting-edge materials support a circular economy. Through the use of nano-sensors for soil monitoring, targeted fertilizer and pesticide application, and improved water management, nanotechnology also makes precision agriculture possible. As a result, the negative consequences of traditional farming methods on ecosystems are minimized and agricultural outputs are raised with less environmental impact. The Clean Environment Concept is depicted below in Figure 4.

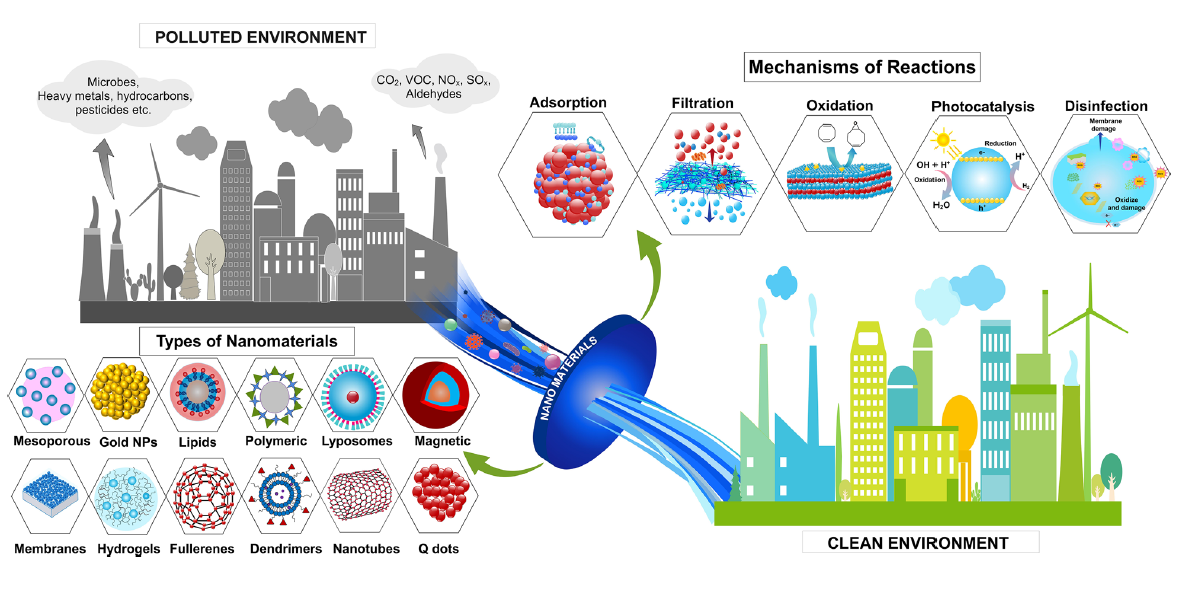


Figure 4: Concept of Clean Environment (Figure Source: Asghar et al., 2024).

Beyond just purification, nanotechnology helps create intelligent irrigation systems that maximize water use and preserve this valuable resource. Nanosensors can also monitor water quality in real-time, giving essential data for optimal resource management and pollution control. These developments are certain to contribute to a greener ecology through the use of green nanotechnology concepts. We reduce unforeseen ecological effects by emphasizing non-toxic ingredients, energy-efficient manufacturing, and waste minimization throughout the lifecycle of nano-enabled goods and processes. The emphasis switches to developing solutions that are both environmentally friendly and technologically sophisticated. The combination of green nanotechnology and nanotechnology ultimately catalyzes systemic change in the direction of a more environmentally friendly global ecosystem. Through the development of tools for cleaner energy, precision agriculture, sustainable materials, and effective water management, this multidisciplinary field enables us to prevent environmental harm, preserve natural resources, and create a future in which ecological health and human activity coexist peacefully.

**UTILIZING NANOTECHNOLOGY TO ADDRESS ENVIRONMENTAL CONCERN**

Using the special qualities of materials at the nanoscale to solve urgent environmental issues is a novel approach. Nanotechnology is very successful at removing pollutants from a variety of media because it has a larger surface area and is more reactive (AZoNano, 2023). For example, the removal of organic pollutants and heavy metals from water and groundwater is highly effective when using nanomaterials such as carbon nanotubes and nanoscale zero-valent iron (nZVI) (CLU-IN, n.d.). Developing and Demonstrating Nanosensor Technology to Detect, Monitor, and Degrade Pollutants demonstrates how nanotechnology also makes it possible to create extremely sensitive nanosensors that can detect pollutants at extremely low concentrations in real time, supporting proactive environmental monitoring and management. Research (n.d.). The goal of green nanotechnology is to minimize waste and energy consumption by synthesizing nanomaterials in ecologically acceptable ways. One example is the production of gold and silver nanoparticles with catalytic and antibacterial qualities using plant extracts (Sher et al., 2022). By creating more effective solar cells and cutting-edge materials for energy storage, nanotechnology also helps to provide cleaner energy. Additionally, by facilitating more effective industrial processes and the development of nanocatalysts to lower hazardous emissions, it helps avoid pollution.

1. **Reducing the number of pollutants generated while processing:**

Researchers have demonstrated that using nanocluster silver as catalysts can greatly lower the toxicity generated in a system used to create propylene oxide, which is another example of this. Common materials, including paint, plastics, detergents, and liquid brakes, are made from propylene oxide.

1. **Increasing the amount of electricity produced by wind turbines:**

Carbon nanotubes with epoxy are used to create air fresheners. Because the resulting blades are robust and lightweight, each windmill produces a significant amount of electricity.

1. **Cleaning up oil spills:**

To spread the oil into perishable components, photocatalytic copper tungsten oxide nanoparticles are used. The grid's nanoparticles have a large response area, are absorbed by sunlight, and are effective in water, which makes them suitable for cleaning up oil spills.

1. **Cleansing natural chemicals that contaminate groundwater:**

Iron nanoparticles have been demonstrated by researchers to be useful in cleaning groundwater of contaminating live solvents. The water's body contains iron nanoparticles, which break down into a living solvent nearby. Compared to treatments involving the disposal of water, this approach may be more cost-effective and efficient.

1. **The production of solar cells that generate electricity at a competitive price:**

According to the study, solar cells with a series of silicon nanowires embedded in polymers are more efficient but also less expensive. This could lead to solar cells producing as much energy as coal or fuel, along with other attempts to enhance solar cells through nanotechnology.

1. **Eliminating airborne volatile organic compounds (VOCs):**

Volatile organic compounds can be broken down at room temperature using a catalyst that researchers have demonstrated. The catalyst is composed of porous manganese oxide with incorporated gold nanoparticles.

1. **Fuel cell-powered vehicles' hydrogen storage:**

A smaller fuel tank and more hydrogen storage are achieved by using graphene layers to boost the hydrogen binding capacity rather than graphene in the fuel tank. This can aid in the development of vehicles that run on hydrogen.

1. **Cutting the price of fuel cells:**

Platinum potency can be increased by altering the way the platinum atoms used in fuel cells are separated. This considerably lowers fuel cell expenses by enabling the fuel cell to operate with less than 80% platinum (Garcia, 2022).

**GREEN NANOTECHNICAL PRACTICES AND PRINCIPLES**

Green nanotechnological ideas and practices are a paradigm change in the development and use of nanomaterials, with the goal of maximizing sustainability while reducing dangers to the environment and human health. Green chemistry and green engineering principles are applied in this field to the design, production, and application of nanoscale materials and technologies. According to Dhingra et al. (2010), the core idea of green nanotechnology is to develop materials and procedures that are safe at every stage of their lifecycle, from obtaining raw materials to recycling or disposal. Finding environmentally acceptable ways to synthesize nanomaterials is one of the main goals of green nanotechnology. Using traditional procedures frequently results in the production of harmful byproducts, high energy consumption, and hazardous substances. As an alternative, green synthesis uses biopolymers, microorganisms (fungi and bacteria), and plant extracts as stabilizing and reducing agents using renewable resources (Alsaiari et al., 2023). For example, metal ions can be reduced into nanoparticles without the need for harsh chemicals thanks to plant phytochemicals like terpenoids and flavonoids. According to Pradeep et al. (2021), microbial processes provide a bio-based method for creating nanoparticles, frequently in mild settings. Designing intrinsically safer nanomaterials is another important idea. This entails taking into account, from the beginning, the toxicity and possible environmental fate of nanomaterials. Their activity in the environment and interactions with biological systems can be influenced by various factors, including size, shape, surface charge, and aggregation state. To lessen any negative effects on the environment or human health, green nanotechnology aims to create nanomaterials with controlled degradation routes, less persistence, and decreased bioaccumulation potential (6. What Are the Potential Environmental Effects of Nanomaterials?, n.d.)

Additionally, the use of renewable energy sources and lowering energy usage during the synthesis of nanomaterials are key components of green nanotechnological techniques. This idea is supported by the use of ambient temperature and pressure conditions, which are frequently found in biosynthetic techniques. Another important consideration is the choice of solvents and auxiliary materials; water, ethanol, supercritical fluids, and other less dangerous substitutes for conventional organic solvents are preferred (Jabeen ET AL., 2024). An essential tool in green nanotechnology is lifecycle assessment (LCA), which allows for a thorough analysis of the environmental effects of a nanomaterial or nano-enabled product throughout its whole life. This entails evaluating waste production, emissions, energy consumption, and resource depletion at every phase, from the extraction of raw materials to end-of-life care. LCA directs the creation of more sustainable nanotechnological solutions by assisting in the identification of possible hotspots and areas for development (Dhingra et al., 2010b). To put it simply, green nanotechnological practices and principles aim to balance the advantages of nanotechnology with human welfare and environmental stewardship. By emphasizing resource efficiency, safer material design, eco-friendly synthesis, and whole lifecycle considerations, this field prepares the way for a time when nanotechnology will help create a more sustainable and greener global ecosystem.

1. **Synthesis of Sustainable Nanomaterials:**

Energy-intensive procedures and hazardous chemicals are frequently used in the conventional synthesis of nanomaterials. Green nanotechnology, on the other hand, focuses on environmentally benign, sustainable processes for creating nanoparticles. The development of environmentally friendly nanomaterial synthesis techniques is guided by several green chemistry concepts, including the utilization of renewable raw materials, energy efficiency, and the reduction of harmful compounds.

* **Synthesis in Biology:** The utilization of biological systems, including bacteria, fungi, algae, and plants, to create nanomaterials is one of the most promising developments in green nanotechnology. "Bio-nanoparticles," or biologically generated nanoparticles, are environmentally benign and frequently have special qualities because of their organic source. For example, non-toxic and biodegradable plant extracts can be used to create silver nanoparticles. By using less hazardous chemicals and solvents, this method makes the process safer and more environmentally friendly.
* **Eco-friendly Reagents and Solvents:** Another key aspect of green nanotechnology is the replacement of harmful chemical solvents with green alternatives. Ionic liquids, supercritical fluids, and water are being explored as eco-friendly solvents for nanoparticle synthesis. These solvents are non-toxic, non-flammable, and recyclable, reducing the environmental impact of nanomaterial production.
* **Energy Efficient Methods:**  Chemical vapor deposition and ball milling are two energy-intensive and waste-producing traditional ways of creating nanomaterials. Green nanotechnology encourages the creation of low-energy, resource-efficient, and waste-reducing procedures. For instance, nanomaterials can be produced more effectively using microwave-assisted synthesis and chemical methods, conserving energy and cutting waste.

1. **Green Nanomaterials:**

Green nanomaterials are materials with little environmental impact that improve performance without harming the environment. These materials can be made from renewable resources or made biodegradable, which lessens the environmental impact of their disposal or release into ecosystems.

* **Nano cellulose:**  Plant-based nanocellulose is a promising green nanomaterial because of its mechanical strength, biodegradability, and renewability. It is employed in many different applications, such as food additives, medicine delivery methods, and as a reinforcing component in composites. Nanocellulose can help cut down on plastic waste and provide an environmentally acceptable substitute for synthetic plastics.
* **Biodegradable Nanomaterials:** Biodegradable nanoparticles reduce the amount of waste that accumulates in the environment by gradually dissolving into innocuous components. For instance, biodegradable nanoparticles made from natural biopolymers like cellulose, chitosan, and starch have a variety of possible uses in environmental remediation, medical devices, and food packaging.
* **Carbon nanomaterials: Carbon-based** nanomaterials, such as carbon nanotubes (CNTs) and graphene, have demonstrated exceptional strength, electrical conductivity, and thermal properties. While they are not inherently biodegradable, ongoing research focuses on designing sustainable methods for their production and improving their recyclability to reduce their environmental impact (Navyashree et al., 2025).

**ADVANCES IN GREEN NANOTECHNOLOGY**

Green nanotechnology, which is based on the ideas of green engineering and green chemistry, offers a variety of uses for promoting environmental sustainability. In environmental remediation, it provides environmentally benign synthetic nanomaterials such as plant-derived nZVI and sustainably produced nano-enabled membranes for enhanced water purification and effective pollutant removal from soil, water, and air. Green pathways to plasmonic nanoparticles and quantum dots improve solar cell efficiency for clean energy generation and storage, while sustainable materials in supercapacitors and nano-enhanced batteries offer safe energy storage. Green nanosensors for precision farming, nano-coatings for food preservation, and green nanofertilizers for regulated nutrient release are all advantages of sustainable agriculture. The potential of green nanotechnology to greatly contribute to a more environmentally conscious future is further demonstrated by the fact that eco-friendly nano-coatings prolong product lifespans, biodegradable nanomaterials decrease waste, and green nanocatalysts increase industrial efficiency in sustainable manufacturing.

1. **Renewable Energy:**

Green nanotechnology is essential to the development of renewable energy technologies because it improves the effectiveness, performance, and environmental sustainability of energy conversion, storage, and generating processes. When used in solar cells, sustainably produced nanomaterials such as silver nanoparticles and quantum dots enhance sunlight absorption over a greater range and improve electron mobility, which results in higher energy conversion rates thanks to environmentally friendly production. Sustainable graphene and carbon nanotubes, as well as bio-derived metal oxides, are among the advanced materials for batteries and supercapacitors that can be made using green nanotechnology for energy storage (Henkel K. 2023). Because of their longer lifespans, faster charging times, and greater energy storage capacity, these materials make renewable energy more reliable for grid integration. Furthermore, sustainable porous nanomaterials are being investigated for safer and more efficient hydrogen storage, while environmentally friendly nanocatalysts—possibly utilizing non-precious metals—improve the efficiency of hydrogen synthesis and conversion in fuel cell technology. Green nanotechnology is a key driver for a cleaner and more sustainable energy future because of its concentration on environmentally friendly synthesis, use of sustainable materials, and enhancement of device performance.

* **Enhanced solar cells: Increasing the efficiency of solar cells is one of the most well-known uses of green nanotechnology in renewable energy. To enhance light absorption and electron transport, solar cell designs can employ nanoparticles like quantum dots and nanowires. In addition to improving total energy conversion efficiency, this makes it possible to create lightweight, flexible solar panels that may be used in a variety of settings (Henkel K. 2023). The performance of solar cells is being improved by nanomaterials, especially those based on semiconductors like perovskite, copper indium gallium selenide (CIGS), and cadmium telluride (CdTe). The production of cleaner and more economical solar energy is made possible by these materials, which boost the efficiency of photovoltaic devices.**
* **Energy Storage:** Nanotechnology has made it possible to create high-performance batteries and supercapacitors with longer lifespans, faster charging times, and better energy densities. In order to create more environmentally friendly and energy-efficient next-generation energy storage devices, like lithium-ion batteries and supercapacitors, green nanomaterials, such as nanostructured carbon materials and nanomaterial-based electrodes, are essential (Navyashree et al., 2025). In order to integrate renewable energy sources into the power system, it is challenging to build high-performance energy storage devices. By using nanostructured materials in batteries and supercapacitors, green nanotechnology makes a contribution. Longer battery lifespans, quicker charging times, and increased energy storage capacity are all results of nanomaterials like graphene and nanotubes increasing the electrode surface area (Henkel K. 2023).
* **Biofuels:** Green Nanotechnology plays a crucial role in stimulating sustainable fuel generation processes. Nanocatalysts promote efficient and selective reactions for the conversion of renewable resources, such as sunlight or biomass, into fuels like hydrogen or biofuels. These nanomaterials help create a more sustainable and greener energy infrastructure by enabling cleaner and more energy-efficient fuel production techniques (Henkel K. 2023). Additionally, nanotechnology is being used to improve the conversion of biomass into usable fuel through the use of nanomaterials. For instance, the production of bioethanol is made more efficient by using enzymes and nanoparticles to speed up the breakdown of cellulose in plant matter (Navyashree et al., 2025).

1. **Environmental Remediation:**

Green nanotechnology has great promise for addressing environmental contamination by developing efficient, reasonably priced, and environmentally friendly remediation techniques. that improve the quality of the environment, scientists can create materials that precisely target and eliminate particular toxins from contaminated soil, water, and air by manipulating them at the nanoscale. For example, functionalized carbon nanotubes and other engineered nanomaterials have a high affinity for adsorbing organic pollutants and heavy metals from water sources, while nanoscale zero-valent iron (nZVI), which is frequently produced using environmentally friendly techniques like plant extracts, can chemically degrade a variety of contaminants in soil and groundwater (Gul et al., 2022). Additionally, the development of sophisticated nanosensors for the highly sensitive and real-time detection of contaminants, even at trace levels, is made easier by green nanotechnology. These sensors can be used for ongoing environmental monitoring, allowing for early contamination detection and prompt intervention. They are frequently made of biocompatible materials. Another important field is the use of photocatalytic nanomaterials, which provide a sustainable and energy-efficient method of purifying air and water by catalyzing the breakdown of organic contaminants into less hazardous chemicals when exposed to sunshine. Utilizing biological entities or softer chemical conditions, green synthesis strategies for these nanomaterials further reduce their environmental impact (Susan et al., 2021). Green nanotechnology offers novel approaches for the detoxification and removal of contaminants such industrial chemicals, insecticides, and heavy metals in soil remediation (Prakash & S, 2023). Nanomaterials can be made to either improve the breakdown of pollutants by catalysis or biological processes, or to immobilize them and stop them from spreading (Del Prado-Audelo et al., 2021). Furthermore, as an environmentally friendly substitute for conventional adsorbents in soil cleaning, nanobiosorbents are made from renewable biological sources. By emphasizing the development of these technologies using green chemistry principles, the remediation procedures themselves are guaranteed to be environmentally sound, supporting a more sustainable approach to pollution control.

* **Air Purification:** In the vital battle against air pollution, nanotechnology proves to be a potent ally, providing creative ways to eliminate toxic materials from industrial emissions. Nanomaterials can efficiently absorb and neutralize harmful gasses and particulate matter when they are created with particular features. Utilizing nanoscale photocatalysts, like titanium dioxide (TiO₂), in sophisticated air purification systems is a perfect illustration. These microscopic powerhouses respond to light by starting chemical reactions that convert toxic gaseous pollutants, such as carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOCs), into less dangerous byproducts. Cleaner industrial operations and better air quality in urban areas are possible thanks to this catalytic degradation at the nanoscale.
* **Water Purification:** Nanomaterials have shown great promise in transforming wastewater treatment and water purification. These include carbon-based nanoparticles such as graphene and carbon nanotubes, magnetic nanoparticles (MNPs), and nanoscale zero-valent iron (nZVI). Because of their special qualities, which include a high surface area-to-volume ratio and adjustable surface functions, they can effectively absorb and eliminate a variety of pollutants. Since carbon-based nanoparticles have porous architectures and surface chemistry, they have great adsorption capabilities for heavy metals and organic contaminants. MNPs, which are frequently functionalized with particular ligands, have the ability to attach to heavy metal ions, pathogens, and other contaminants in a selective manner. Their magnetic characteristics make it simple to separate and collect the treated water using external magnetic fields, providing a reusable and affordable solution. Through redox processes, nanoscale zero-valent iron (nZVI), especially when produced using environmentally friendly techniques, has demonstrated remarkable efficacy in the destruction of a range of organic pollutants, such as dyes and chlorinated chemicals. Additionally, these nanoparticles can be included into sophisticated filtering membranes to improve their ability to remove dissolved materials, bacteria, and particulate matter, so promoting effective and sustainable access to clean water and pollution management.
* **Soil Remediation:**  Green nanotechnology plays a key role in decontaminating soil as well. Iron, silica, and clay nanomaterials are among the many that can be successfully added to soil to chemically neutralize, absorb, or immobilize a variety of contaminants, including hazardous heavy metals, persistent insecticides, and hazardous industrial wastes. For instance, silica and clay-based nanomaterials provide high surface areas for the adsorption and stabilization of heavy metals, preventing their leaching into groundwater and uptake by plants, while iron-based nanoparticles can aid in the redox reactions that break down organic contaminants. The potential for biodegradation of several of these nanomaterials is a major benefit in soil remediation. They provide a more environmentally responsible and sustainable method of reclaiming polluted land for ecological or agricultural uses since they gradually decompose into less hazardous components, reducing the possibility of long-term buildup of foreign contaminants in the soil ecosystem. This emphasis on biodegradable materials is in line with the fundamental ideas of green nanotechnology, guaranteeing that the remediation procedure itself eventually leads to a cleaner environment (Alkhaza’leh et al., 2025).

1. **Sustainable Manufacturing:**

Green nanotechnology addresses important issues such as energy consumption, waste creation, and the usage of hazardous compounds in industrial processes, providing important avenues for sustainable manufacturing. Green synthesis of nanomaterials, which frequently uses biological entities such as plant extracts or microbes, uses less energy and produces fewer harmful byproducts than standard chemical synthesis methods. The creation of more effective catalysts, or nanocatalysts, is another benefit of nanotechnology. These catalysts can greatly increase reaction speeds in a variety of industrial processes, resulting in less waste and less energy consumption. For example, chemical synthesis can be made more efficient by nanocatalysts, which can also make processes cleaner and use less resources (*Green Nanomaterials for Industrial Applications*, n.d.). Green nanotechnology also encourages the use of biodegradable and renewable nanomaterials, like plant-based nanocellulose, as substitutes for traditional, less sustainable materials in a variety of applications. This lessens the environmental impact of end-of-life products and reduces dependency on limited resources. Green nanotechnology offers creative answers for developing more ecologically conscious and financially feasible manufacturing processes across a range of industries by emphasizing eco-friendly synthesis, resource efficiency, and the creation of sustainable nanomaterials (Rickerby, 2013).

* **Nanocoatings:** Nanocoatings derived from eco-friendly materials are being used more and more to improve the performance and longevity of a variety of items, including metals, textiles, and electronics. These incredibly thin layers offer remarkable resistance to contamination, wear, and corrosion and are frequently molecularly tailored. These nanocoatings drastically increase the longevity of the underlying materials and final products by serving as a protective barrier, which lowers the need for frequent replacements and the waste and resource consumption that go along with them. This strategy promotes product longevity and reduces the environmental impact of product creation and disposal, which is consistent with the principles of sustainable manufacturing. As an ecologically friendly substitute for conventional coatings that could include hazardous chemicals or necessitate energy-intensive application procedures, the creation of nanocoatings from non-toxic and environmentally benign materials enhances their sustainability advantages (Reports, 2024).
* **Nanocatalysis:** Nanocatalysts greatly increase reaction speeds and reduce energy consumption, making them increasingly important in supporting sustainable chemical processes. To produce necessary materials like fuels, chemicals, and plastics, these catalysts at the nanoscale provide a greater surface area and special electrical characteristics that allow for more effective chemical transformations. Because of this increased efficiency, reactions can frequently be carried out in milder environments, requiring fewer high temperatures and pressures. This lowers energy requirements and the resulting environmental effects. Additionally, nanocatalysts frequently have improved selectivity, which means that they reduce the production of undesirable byproducts while increasing the production of the intended product. Cleaner production techniques with less waste output and easier downstream processing result from this enhanced selectivity, which is entirely consistent with the ideas of green chemistry and sustainable manufacturing. An additional factor in their sustainability profile is the creation of nanocatalysts from ecologically friendly materials and their potential for simpler recovery and reuse (Navyashree et al., 2025).

In the pursuit of sustainability, green nanotechnology is an exciting new frontier. Green nanotechnology provides creative answers for some of the most important environmental issues facing the globe today, from waste management and pollution to the generation of renewable energy, by fusing the power of nanomaterials with environmentally beneficial ideas. Green nanotechnology has the potential to completely transform industries and help create a more sustainable and ecologically sensitive future as long as research and new applications continue. To fully achieve its promise, however, issues with public perception, scalability, and safety must be resolved (Navyashree et al., 2025).

**NANOTECHNOLOGY AND WASTE MANAGEMENT**

A major environmental problem is the increasing amount of solid waste produced by population increase and changing lifestyles, which releases a variety of dangerous organic and inorganic pollutants into the air, water, and land. These ubiquitous pollutants are frequently difficult to remove with traditional procedures. To address this pressing issue, the application of cutting-edge techniques, including nanotechnology, holds great promise. Numerous nanomaterials are being used more and more in waste management, such as reactive nanoparticles for targeted contaminant remediation, sensitive nanosensors for real-time environmental monitoring, strong nanophotocatalysts for the breakdown of organic pollutants, and extremely effective nanofilters for pollutant removal.

* **Nanophotocatalysts and nanoporous catalysts:**

When exposed to sunshine, a substance known as a photocatalyst produces a chemical reaction without changing. These substances just create the necessary circumstances for the reaction; they are not actively involved in oxidation and reduction reactions. Titanium dioxide possesses nearly every quality that makes it an ideal photocatalyst. When titanium dioxide is exposed to water, oxygen, and ultraviolet light, it generates free radicals, which can break down a variety of hazardous substances into less toxic carbon compounds (Taran et al., 2020). Titanium dioxide nanoparticles (TiO2) are more efficient at breaking down organic pollutants than their larger counterparts because of their higher surface area to volume ratio and improved photocatalytic capabilities. This substance is used in several ways to remediate leachate from waste material landfills, such as covering fixed membranes, integrating into nanocrystalline microspheres, and forming composite membranes with silica. The natural hydrophilia of titanium dioxide also helps it interact with and break down a variety of organic pollutants found in leachate. Furthermore, it can break down complicated chemical molecules into less dangerous substances because of its photocatalytic activity, which is frequently boosted under UV or even visible light depending on how it is modified (Li et al., 2020).

TiO2 nanoparticles' main strength is in oxidizing organic contaminants, however, some studies also show that they can adsorb heavy metals from wastewater to some degree. The main mechanism is the photocatalytic destruction of organics. The use of TiO2 nanoparticles, particularly those produced using environmentally friendly processes, presents a viable path for effective and sustainable leachate treatment, helping to safeguard the environment and water supplies (Engates & Shipley, 2010). Ethanol may be produced from the wastes using porous nanocatalysts. The gasification process, which uses high pressure and temperature in a controlled setting to transform carbon compounds into syngas, is employed for this purpose. When porous nanocatalysts are present, syngas is transformed into ethanol. Carbon monoxide, hydrogen, and trace amounts of carbon dioxide and methane make up the majority of syngas. Ethanol is produced by syngas's carbon monoxide molecules. By providing favorable circumstances for the synthesis of ethanol, nanocatalysts can improve the absorption of these molecules (Taran et al., 2020).

* **Nanofilters in waste management:**

In waste management, especially in wastewater treatment, nanofilters-in particular, nanofiltration (NF) membranes-are essential. Using size exclusion and electrostatic interactions, they selectively eliminate organic molecules, multivalent ions, and some microbes with pore diameters ranging from ultrafiltration to reverse osmosis. According to science, NF has benefits including high permeability, superior removal effectiveness for particular impurities (such as colors and heavy metals), and comparatively less energy usage than reverse osmosis. Different NF membrane types (polymeric, inorganic, and composite) are designed for certain uses, such as water softening in wastewater, landfill leachate purification, and industrial effluent treatment. They are a promising technology for environmentally friendly water recycling and pollution management, and their efficacy is dependent on membrane composition, pore size, surface charge, and operating parameters including pH and pressure (Mohammad et al., 2004).

The presence of toxic and nonbiodegradable substances in wastes and their leachate, such as heavy metals, ammonia, xenobiotic organic compounds, arsenic, and inorganic macrocomponents, has made it impossible for normal biological and physicochemical techniques to completely eradicate them at environmental standards. Thus, pretreatment, posttreatment, and contemporary technology are taken into account when eliminating pollutants from the environment. Trash can be treated with nanofiltration without the use of chemicals, which reduces the cost of transportation and disposal of concentrated and intense trash. By using nanofilters, 60–70% of the COD and 50% of the ammonium in the leachate can be eliminated. According to Taran et al. (2020), nanofilters can be used to remove a variety of contaminants from wastewater, including pathogens, uranium, chromium, arsenic, anions, and cations. It is necessary to regulate the quantity of deposits on the filtration membrane while using nanofiltration technology. Cleaning or replacing the membrane, which is costly and time-consuming, is one easy way to deal with the dilemma of fouling. Utilizing substances like fullerenes that can stop biological fouling is a practical approach. It is also possible for bacteria and other germs to adhere to one another and build up on the filtering membrane and within the pipes. Bacteria and other microbes gradually take up other organic molecules and form an organic layer that can obstruct the membranes. Additionally, fullerenes can be effective as membrane antifouling agents by stopping bacterial respiration. As medications that break up clots, fullerenes can keep pipes and filtering membranes clear. According to Taran et al. (2020), applying these nanoparticles to pipes and membranes can be an effective way to stop biological fouling.

**NANOTECHNOLOGY: REVOLUTIONIZING WATER AND WASTEWATER**

The availability of clean water is one of the largest problems facing humanity, even though water covers almost three-quarters of the planet's surface. Modern equipment that swiftly transforms contaminated water into drinkable water must be used to increase the effectiveness of water treatment systems. Because of nanotechnology, fewer contaminants from human activity are entering the environment and waterways. Utilizing carbon nanotubes, nanofilters, nanoparticles, nanophotocatalysts, nanoclays, and nanofilters in water treatment, as well as bionanosensors for prompt water pollution detection, are the most significant environmental uses of nanotechnology (Taran et al., 2020). Figure 5 below provides some information about the use of nanotechnology in water treatment.

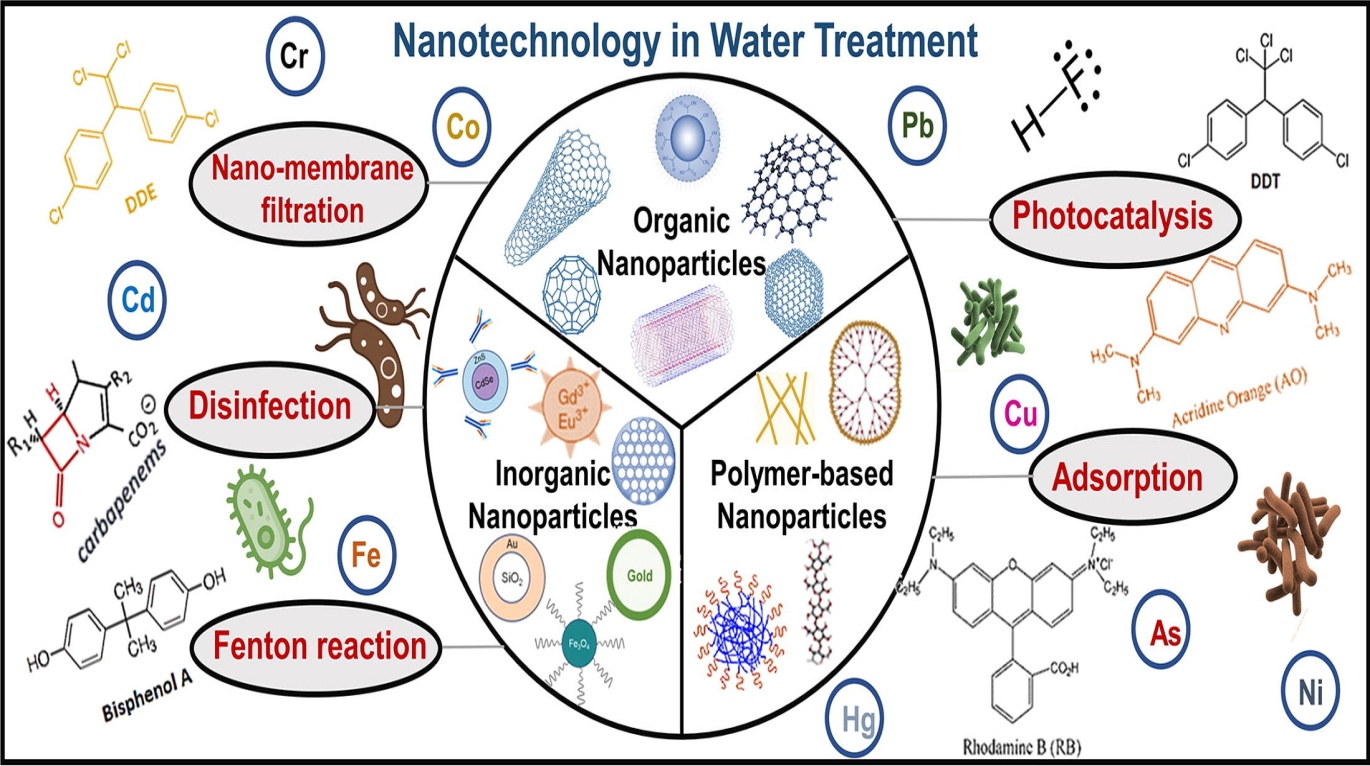


Figure 5: Nanotechnology in Water Treatment (Figure Source: Ajith et al., 2021)

According to Yaqoob et al. (2020), nanotechnology provides revolutionary solutions for the treatment of water and wastewater because of the special physicochemical characteristics of nanoparticles. Their large surface area-to-volume ratio improves their adsorption and reactivity, which makes them more effective at removing pollutants than traditional techniques (Roy et al., 2021). A variety of nanomaterials are used, such as carbon-based nanoparticles (such as graphene and carbon nanotubes) for the adsorption of heavy metals and organic pollutants (Isaeva et al., 2021). Often functionalized, magnetic nanoparticles make it simple to separate and remove contaminants selectively. A variety of organic contaminants can be efficiently broken down by nanoscale zero-valent iron (nZVI) via redox processes (Liu et al., 2024). Pathogens, chemical compounds, and ions are all selectively eliminated by nanofiltration membranes with carefully regulated pore diameters. When exposed to light, nanocatalysts such as titanium dioxide nanoparticles help break down organic contaminants (Wikipedia contributors, 2025). Real-time water quality monitoring is made possible by nanosensors, which enable prompt action (Nanosensors in Detecting and Monitoring Water Pollutants, n.d). The increasing global problems of pollution and water shortages may be addressed by these nano-based methods for wastewater treatment and water purification, which have the potential to be more effective, economical, and sustainable (Pérez et al., 2023).**Nanofilters:**

Microfiltration (100 nm), ultrafiltration (10 nm), nanofiltration (1 nm), and reverse osmosis (<1 nm) techniques can all be applied, depending on the kind and size of separable components. In terms of diameter, nanofilters fall between reverse osmosis and ultrafiltration techniques. The reverse osmosis method creates more purity than is required, and the ultrafiltration method contains more pollutants than is permitted. As a result of its high price, it has certain drawbacks. By using less energy and having a better water penetration rate than other methods, filters employed in the nanofiltration process can cleanse contaminated water at the right volume and desired quality. When these filters come into contact with any living structure, the high surface energy of the nanoparticles, as zinc and silver-coated on the filter, destroys it. The process of nanofiltration involves size-based separation, and the smallest viruses cannot pass through filters with nanopores. Utilizing active substances like titanium dioxide or silver nanoparticles along with UV light sources might enhance this impact by eliminating imprisoned bacteria, fungi, and viruses. The filter will be able to separate more material because its pores are narrower. When comparing nanofilters to other filters, their ability to remove ions with selectivity is crucial. Hazardous materials are eliminated, and minerals essential to human health are kept in the water by employing nanofilters (Taran et al., 2020).

1. **Nanoparticles:**

Compared to bigger particles, nanoparticles have a higher capacity for adsorption and a much better interaction with contaminants because of their much larger surface area-to-volume ratio. According to Wikipedia editors (2025b) and PMC, "Chemical Basis of Interactions Between Engineered Nanoparticles and Biological Systems (Mu et al., 2014)," this characteristic, in addition to their capacity to interact with different chemical functional groups, enhances their affinity for desired molecules. Because of these qualities, nanoparticles are a suitable instrument for cleaning contaminated water and absorbing toxins. Metal nanoparticles are thought to be highly effective, selective adsorbents that can adsorb a wide range of metal ions and anions. Many environmental issues may be resolved with iron nanoparticles, which are regarded as a new generation of biological monitoring technology. Polluting substances like dioxins, PCBs, trichloroethylene, and carbon tetrachloride are broken down and oxidized by these nanoparticles, which then transform them into less hazardous carbon compounds.

Compared to bigger particles, nanoparticles have a much wider surface. Furthermore, these particles can interact with different chemical groups, which increases their affinity for the substances of interest. These properties make nanoparticles a suitable instrument for treating contaminated water and absorbing contaminants. Metal nanoparticles, which are chosen adsorbents with a high capacity to adsorb a variety of metal ions and anions, are one type of nanoparticle taken into consideration in the adsorption of contaminants. Silver, lanthanum, manganese oxide, zinc oxide, gold, and iron nanoparticles are the most significant metal nanoparticles utilized in the treatment of water and wastewater. Zero-valent iron (ZVI) nanoparticles are the most important metal nanoparticles in the treatment process because they are abundant, inexpensive, harmless, and react quickly with contaminants. Iron nanoparticles are thought to be a promising new biological monitoring technology that can help with a variety of environmental issues. Polluting substances like dioxins, PCBs, trichloroethylene, and carbon tetrachloride are broken down and oxidized by these nanoparticles, which then transform them into less hazardous carbon compounds. Groundwater is treated both in situ and out of situ using neutral iron nanoparticles (nZVI). These nanoparticles can be utilized in filters for external applications or directly injected for subterranean sources for in situ treatment. These bimetallic particles' high activity, long breakdown time, and decreased generation of hazardous compounds were their advantages. However, the toxicity of catalyst metals and the formation of a thick layer that deactivates the catalyst's surface are issues. Bimetallic compounds with nanostructures, such as zinc-palladium, iron-palladium, and iron-silver, have many uses in the refinement of environmental contaminants (Taran et al., 2020).

1. **Nanophotocatalysts:**

Chemicals called nanophotocatalysts are crucial for treating water. Nanophotocatalysts like TiO2 transform a variety of contaminants found in industrial effluent, including amide compounds, cyanide compounds, alcohols, amine compounds, alkanes, alkynes, ethers, aldehydes, and ketones, into carbon dioxide and water. In the presence of oxygen, water, and ultraviolet light, titanium dioxide generates free radicals that can break down pollutants into less harmful forms. The effectiveness of nanophotocatalysts in water treatment is dependent on the pH, oxygen content, and degree of contamination (Taran et al., 2020). To treat water, the powdered nanophotocatalysts can be employed in suspensions as silica-mixed membranes, nanocrystalline microspheres, or other forms. After treatment, suspended nanopowders are challenging to separate. To separate these particles, ultrafiltration or microfiltration is employed. But in the process, a sizable portion of these particles are destroyed. For water treatment, it is preferable to use photocatalysts in the form of nanocrystalline microspheres since they are readily recyclable in this form.

1. **Carbon nanotubes:**

Composed of carbon atoms organized in single or multi-walled configurations, carbon nanotubes are hollow ring structures. Carbon nanotubes can be used to gather data on environmental contaminants and trace contamination. Making nanotube and nanosieve membranes is the main way that nanotubes are used in water treatment. According to Kaur (2018), carbon nanotubes are buckytubes with cylinder-shaped carbon molecules and special properties that make them useful in a variety of applications. These properties include mechanical, electrical, and thermal properties, as well as a structure resembling fullerene and graphene sheets that contain sp2 hybridization of every carbon atom. Figure 6 below shows the eight carbon allotropes.

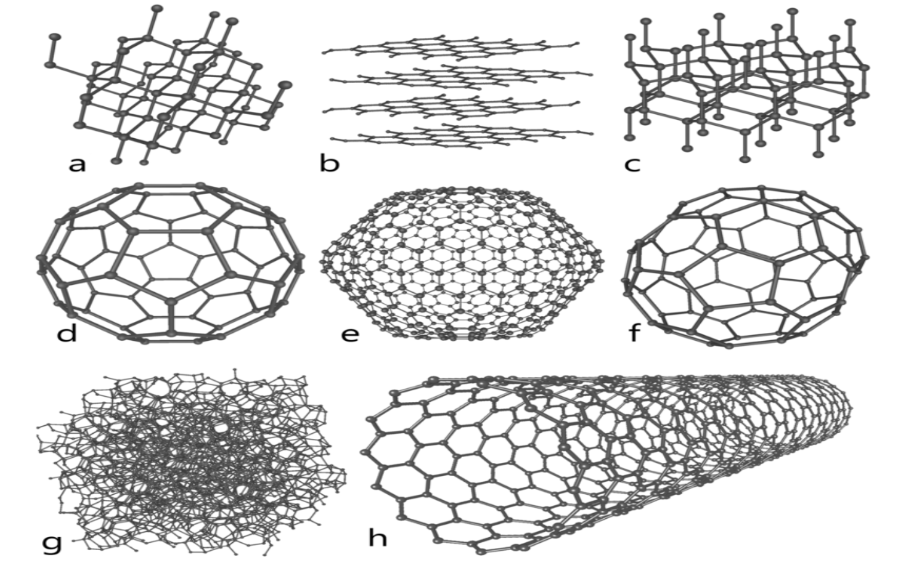


Figure 6: Eight allotropes of carbon, a) Diamond, b) Graphite, c) Lonsdaleite, d) C60 Buckminsterfullerene, e) C540, Fullerite, f) C70, g) Amorphous Carbon, and h) Single-Walled Carbon Nanotube (Figure Source: Iijima & Ichihashi, 1993)

Due to their polymer composition, most membranes have issues and are unable to properly balance the membrane's input and selectivity. The membranes of nanotubes offer suitable selectivity at high inputs. Almost all water contaminants may be removed using these membranes. Because of the nanometric porosity of nanotubes, these filters are more selective than other water treatment methods. Coupled carbon nanotubes positioned on a flexible and porous substrate make up nanosieves. Nanotubes can be positioned beneath a flat or tubular substrate to create filters that resemble paper. Based on this technique, many portable filters are designed to treat water. Some of these filters, called "water sticks," are pencil-sized and can purify one liter of water in ninety seconds. These filters can handle roughly 300 liters of water throughout their useful lives; this capacity could be raised with pre-filtration changes (Taran et al., 2020).

1. **Nanosensors:**

Nanosensors are minuscule instruments capable of detecting and reacting to stimuli at the nanoscale. Using nanotechnology is crucial in this area since measurements at the molecular and atomic level are required. Extraordinary sensitivity and selective function are features of sensors made at the nanoscale. Controlling the disagreeable smell of treated water is one use for nanosensors. Odors emerging from wastewater treatment have been shown to contain a variety of substances, such as organic acids, aldehydes, ketones, or reduced sulfur or nitrogen compounds. Commercial sensors known as "electronic noses" have been developed to identify the types of aromas produced by a mixture of steam gathered in a closed container, as well as to detect microbes and heavy metals in drinking water (Taran et al., 2020). The nanosensor classification based on the sensing event is displayed in Figure 7 below.

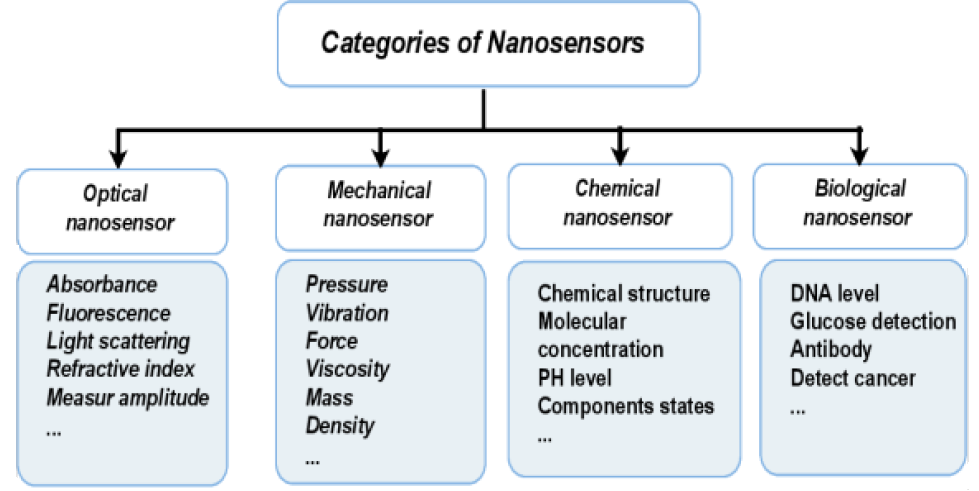


Figure 7: Nano-sensor classification according to the sensing event (Figure Source: Oukhatar et al., 2021).

Material characteristics can change significantly at the nanoscale. The development of environmental compatibility is one of the benefits that could result from this. Given the benefits and diverse uses of nanotechnology, it can be applied globally in several environmental domains, including waste management, fighting water scarcity, lowering and managing air pollution, and other situations, as contemporary science. However, there are difficulties in predicting and identifying safety and environmental issues due to changes in nanoscale characteristics. Therefore, potential dangers should be taken into account while adopting nanotechnology (Taran et al., 2020).

**NANOTECHNOLOGY AND GREEN NANOTECHNOLOGY FOR A GREENER GLOBAL ECOSYSTEM**

The environmental problems facing our globe are extraordinary and include pollution, resource depletion, and climate change. Innovative approaches are needed to solve these complicated problems, and nanotechnology and its sustainable equivalent, green nanotechnology, are in the vanguard of this effort. With the ability to manipulate matter at the nanoscale (one billionth of a meter), these fields provide effective instruments for creating a more environmentally friendly global ecosystem (Insight 1: Green Nanotechnology Enhancements in Manufacturing Sustainability, n.d.). In its broadest sense, nanotechnology offers a multitude of uses for environmental sustainability. Pollution control could be revolutionized by nanomaterials with special characteristics and increased surface area. Nanoparticles, for example, can function as extremely powerful catalysts to degrade air and water pollutants, providing quicker and more efficient remediation than traditional techniques. Consider filters that have these small powerhouses installed in them, able to eliminate even minute levels of dangerous pollutants (Azeez et al., 2023). The water remediation nanoparticles are depicted in Figure 8 below.

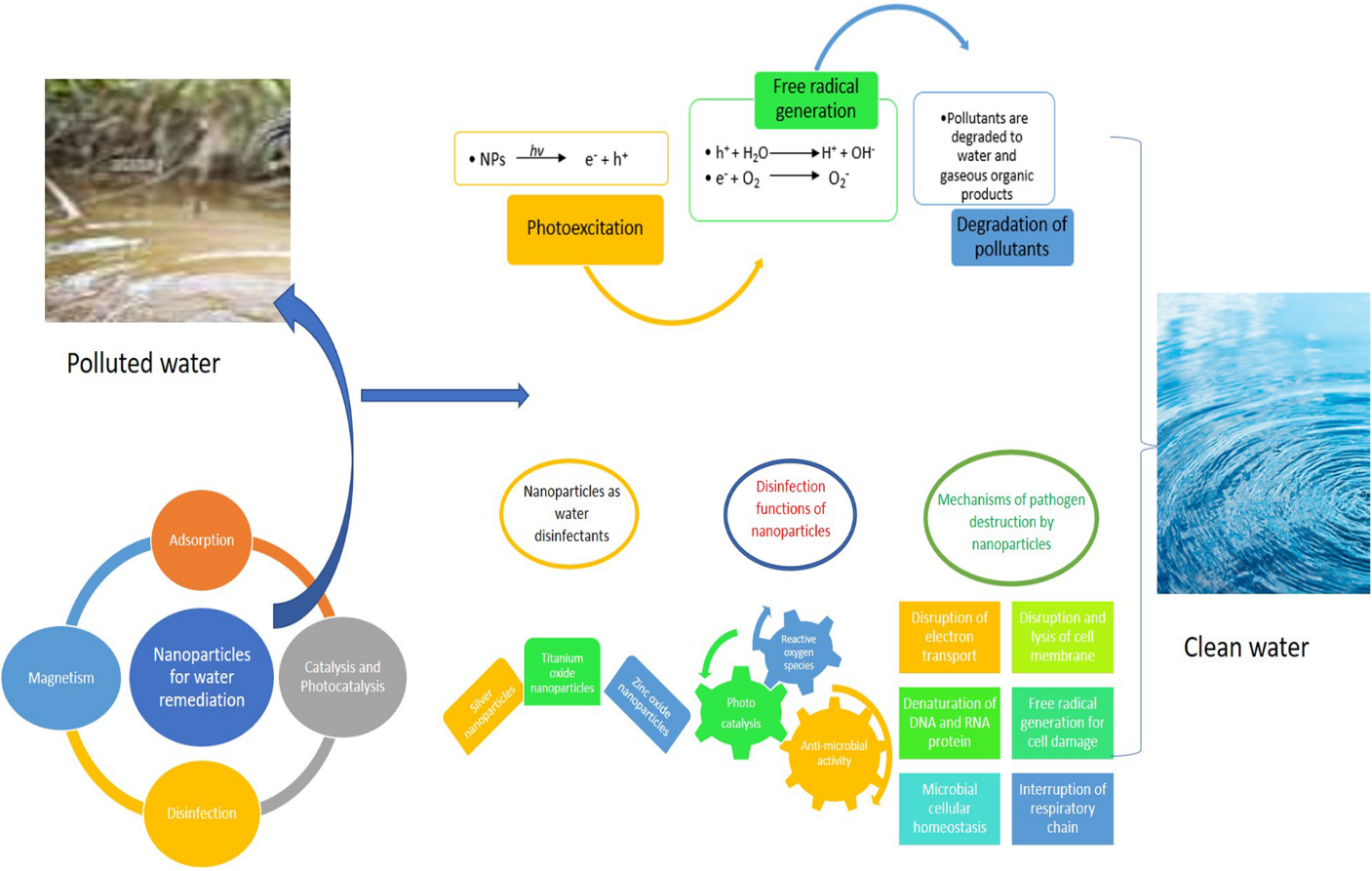


Figure 8: Nanoparticles for Water Remediation (Figure Source: Azeez et al., 2023).

Since the environment is essential to human life, everyone involved should make safeguarding it from harmful pollutants their priority. Although lowering waste production has been beneficial, more waste will be produced as the world's population rises. The sustainable environment is negatively impacted by tons of rubbish that environmental matrices unintentionally and intentionally receive. Both human health and the ecosystem are impacted by the pollutants these activities produce. Macroaggregated materials and microorganisms are used in traditional remediation processes, which include chemical, physical, and biological methods, to break down or eliminate contaminants. Unwanted drawbacks include high cost, difficult disposal, upkeep, and the development of secondary pollutants. Furthermore, removing various contaminants requires several steps of treatment, which takes time. The need to get beyond these restrictions and move toward more environmentally friendly methods raised the possibility of using nanotechnology. The complete breakdown of contaminants without secondary contamination is the current application of nanomaterials in environmental rejuvenation. Because nanoparticles have large, adjustable reactive sites for disinfection, photocatalysis, and adsorption, they are more effective at cleaning up contaminants. Since the types of pollutants and their concentrations in water vary, nanoparticles serve more purposes in water remediation (photocatalysis and disinfection) than adsorption. Their surface shape, surface reactivity, and magnetism improve their fundamental adsorption function, but their disinfection power, which is boosted by their capacity to release ions quickly enough to render germs inactive, is unmatched by traditional disinfectants. Chlorine, ozone, chlorine dioxide, chloroamines, and ultraviolet (UV) radiation are commonly employed for disinfecting water; however, their drawbacks include the need for a complementary process, the production of hazardous byproducts, and their inefficiency against all bacteria. Because of their remarkable capabilities, nanoparticles can inactivate pathogens by rupturing their cell membranes and producing reactive oxygen species (Azeez et al., 2023). The characteristics of nanoparticles that are crucial for water purification are depicted in Figure 9 below.

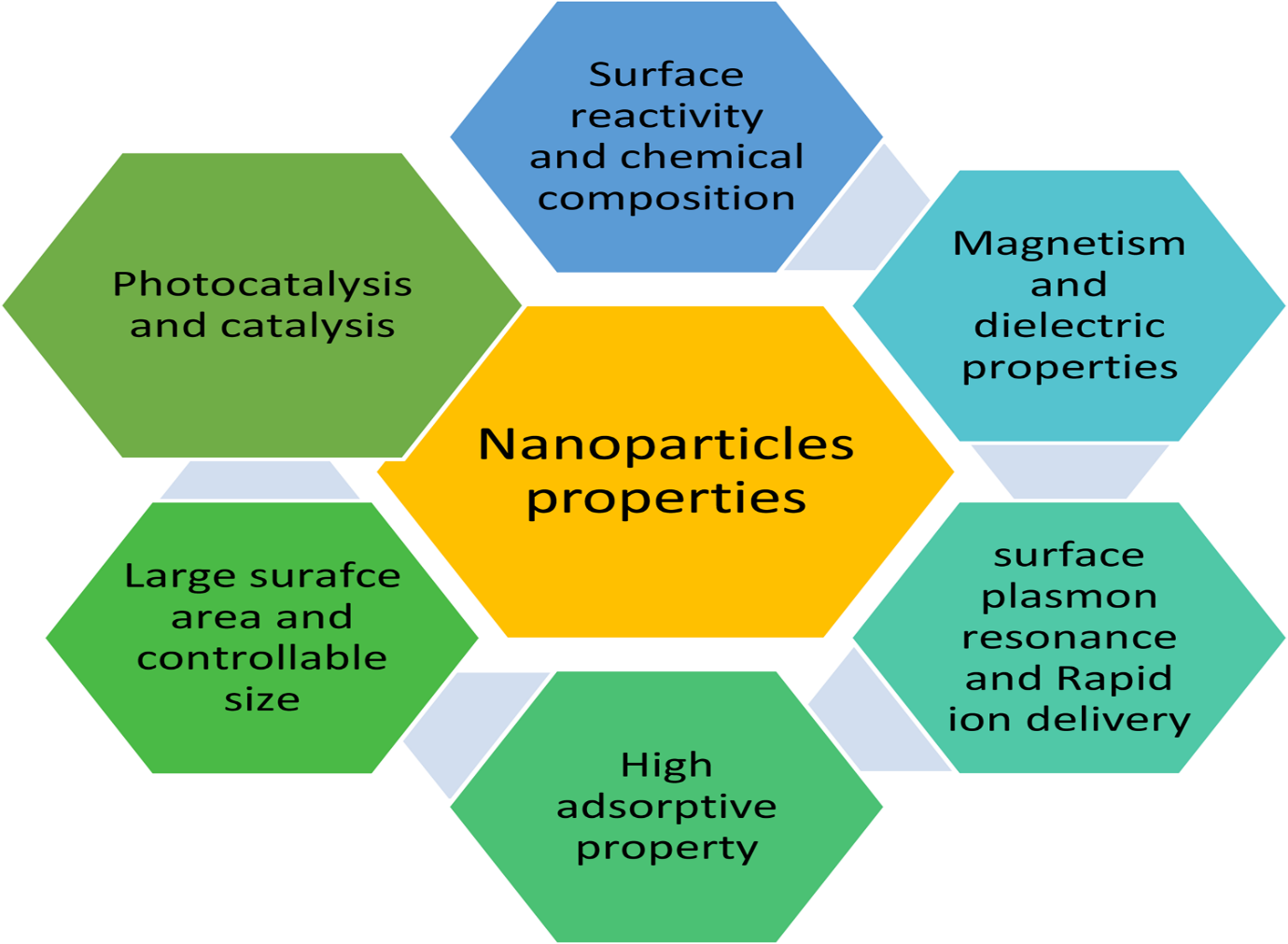


Figure 9: Nanoparticle properties essential for water cleanup (Figure Source: Azeez et al., 2023).

Additionally, developing innovative materials with improved energy efficiency depends heavily on nanotechnology. Increased light absorption from solar panels coated with nano-coatings can result in more effective energy production. Nanomaterials in energy storage are making it possible to develop batteries that are lighter, stronger, and charge more quickly—a development that is essential for the broad use of electric cars and renewable energy systems. Additionally, lightweight nanocomposites are being used in transportation to cut emissions and fuel consumption (Saharudin et al., 2023). Some nanomaterials' manufacture and use, however, present health and environmental risks. Herein lies the role of green nanotechnology. The focus is on creating, producing, and using nanomaterials and nanoproducts in a sustainable and ecologically friendly way. According to Narayanan and Bhaskar (2024), green nanotechnology makes use of renewable resources, minimizes waste, and uses less energy during production.

The creation of bio-inspired nanomaterials is a crucial component of green nanotechnology. To develop sustainable alternatives, scientists are turning to nature's inventive solutions. For instance, by employing nanoparticles to replicate the self-cleaning qualities of lotus leaves, water-repellent and self-cleaning surfaces have been developed, which lessen the need for harsh cleaning agents. Utilizing bio-based nanoparticles made from renewable resources like chitosan, starch, and cellulose is another exciting field. By providing less hazardous and biodegradable substitutes for traditional nanomaterials, these materials lessen their impact on the environment. Consider packaging materials composed of naturally decomposing plant-based nanocellulose, which would reduce the amount of plastic trash produced. Creating greener and more energy-efficient methods for producing nanomaterials is another goal of green nanotechnology. In contrast to conventional chemical synthesis techniques, bio-synthesis routes utilizing microorganisms or enzymes are frequently less energy-intensive and produce less hazardous waste (Green Nanotechnology: Pioneering Sustainable Solutions in Materials Science - Advent Research Materials, 2025).

The application of nanotechnology and green nanotechnology extends across various sectors crucial for a greener ecosystem:

* **Water Purification:** Clean water can be obtained by effectively removing impurities such as organic pollutants, pathogens, and heavy metals using nanofiltration membranes and adsorbents based on nanomaterials.
* **Agriculture:** Waste and the impact on the environment can be decreased by using nanosensors to monitor soil conditions and more effectively apply pesticides and fertilizers. Food waste can be reduced and food shelf life increased with nano-enabled packaging.
* **Renewable Energy: Cleaner energy generation and storage are made possible by nanomaterials, which increase the efficiency of fuel cells, solar cells, and thermoelectric devices.**
* **Air Pollution Control: Urban air quality can be improved by using nanocatalysts in filters and coatings to break down dangerous gases and particulate matter.**
* **Waste Management: Through the creation of biodegradable nanomaterials for packaging and nanocatalysis, nanotechnology can help transform trash into useful resources.**

To sum up, nanotechnology has enormous potential to improve the world ecosystem. To guarantee that these potent instruments are created and used sustainably and responsibly, it is imperative to adopt the tenets of green nanotechnology. We can use the transformative power of the nanoscale to create a more sustainable and healthy future for everybody if we concentrate on bio-based materials, eco-friendly synthesis, and reducing environmental effects throughout the lifecycle of nanomaterials. One step starts a thousand kilometers, and in this instance, the secret to a huge leap towards a greener planet lies in many tiny steps.

**RISK ASSESSMENT AND MITIGATION IN GREEN NANOTECHNOLOGY**

Although green nanotechnology holds promise for sustainable solutions, it requires careful risk assessment and mitigation techniques, with a particular emphasis on comprehending the toxicity of nanomaterials. This proactive strategy is essential for responsible innovation and reducing any potential negative effects on the environment and human health. Because of their special size-dependent characteristics, nanomaterials may behave toxicologically differently than their bulk counterparts. Clarifying the mechanisms of nanotoxicity, which entail intricate interactions at the molecular and cellular levels, is a growing focus of research efforts. The size, shape, surface charge, and composition of nanomaterials are all important factors that affect how likely they are to cause oxidative stress, inflammation, and genotoxicity.

Strict toxicity testing procedures are being created to allay these worries, using both in vitro and in vivo models. High-throughput screening capabilities provided by in vitro investigations enable quick assessment of a variety of nanomaterials and exposure conditions. Cell cultures are frequently used in these investigations to evaluate endpoints like cytotoxicity, genotoxicity, and inflammatory reactions. More thorough information about the systemic impacts of nanomaterial exposure, including their distribution, metabolism, and excretion, can be obtained through in vivo research, which is carried out in animal models. Additionally, methods from computational toxicology are becoming useful for forecasting the toxicity of nanomaterials. In order to reduce the need for extensive experimental testing, researchers can uncover important physicochemical qualities that correlate with toxicity by utilizing quantitative structure-activity relationship (QSAR) models and other computational tools. Effective risk mitigation techniques are crucial for reducing possible exposures in addition to toxicity evaluation. These tactics cover every stage of a nanomaterial's life cycle, from synthesis and handling to usage and disposal. In order to protect employees from inhalation and skin exposure, control methods like containment, ventilation, and personal protection equipment are essential in work environments. Techniques to stop the discharge of nanomaterials into the environment are crucial in the environmental context. This covers the creation of nanomaterials with improved stability and decreased mobility in addition to the application of efficient waste management techniques. Nanomaterials' long-term environmental impact can be further reduced by designing them to be recyclable and biodegradable. By prioritizing comprehensive risk assessment and implementing robust mitigation strategies, the responsible development and application of green nanotechnology can be ensured, paving the way for a sustainable future.

**RESULTS AND DISCUSSION**

The study's findings demonstrate how nanotechnology has enormous potential to transform water and wastewater treatment and support a more sustainable global ecosystem when combined with green nanotechnology principles. Nanoparticles' superior performance in a range of applications is supported by their distinct physicochemical characteristics, especially their high surface area-to-volume ratio. The higher effectiveness of nanoparticles in eliminating a wide range of contaminants from water is a significant discovery. In line with earlier studies on their remarkable adsorption capabilities, carbon-based nanoparticles, such as graphene and carbon nanotubes, exhibit a high affinity for adsorbing organic contaminants and heavy metals. Functionalized magnetic nanoparticles solve a major problem with conventional treatment techniques by providing the benefits of easy separation and selective pollutant removal. Further demonstrating the potential of nanotechnology to address resistant pollutants is the ability of nanoscale zero-valent iron (nZVI) to efficiently breakdown a variety of organic contaminants through redox reactions. Nanofiltration membranes are a major development in separation technology because of their carefully regulated pore diameters. The findings suggest that nanofiltration provides a compromise between the partial separation provided by ultrafiltration and the high purity attained by reverse osmosis, albeit at the expense of increased energy requirements. By adding nanoparticles like silver and zinc to these membranes, their antibacterial qualities are improved, exhibiting a multipurpose method of water purification. The potential for nanoparticles (such as silver or titanium dioxide) and UV radiation to work together to eradicate confined microbes improves these systems' disinfection capabilities.

The study shows how adaptable nanoparticles are in solving a range of environmental problems. TiO2 and other nano photocatalysts efficiently break down organic pollutants into less dangerous forms, demonstrating its promise for cleaning industrial effluent. However, variables like pH, oxygen content, and pollutant concentration affect how well these catalysts work, underscoring the necessity of tuning in particular applications. Because of their special structural characteristics, carbon nanotubes have showed promise as materials for highly selective water treatment membranes. Real-time water quality monitoring is possible with nanosensors, allowing for quick contamination identification and prompt remediation. The study emphasizes the wider uses of nanotechnology in fostering a more environmentally friendly global ecology, going beyond water treatment. Renewable energy technology could undergo a revolution with the creation of nanomaterials with improved energy efficiency. For example, solar panels with nanocoatings can absorb more light, improving energy conversion. The development of sophisticated energy storage systems, including batteries with greater energy densities and quicker charging rates, also heavily relies on nanomaterials. Lightweight nanocomposites have the potential to lower greenhouse gas emissions and fuel consumption in transportation. Nonetheless, the study highlights that following the guidelines of green nanotechnology is necessary for the effective and long-term application of nanotechnology. A change to more sustainable procedures is required due to the possible health and environmental hazards connected to the production and use of specific nanomaterials. Green nanotechnology promotes the creation, manufacturing, and use of nanomaterials in ways that optimize resource efficiency and reduce their negative effects on the environment. This covers the utilization of bio-based materials, the creation of environmentally friendly synthesis techniques, and the decrease in waste production. One important component of green nanotechnology is the creation of bio-inspired nanomaterials that imitate natural processes. For instance, the development of lotus leaf-inspired self-cleaning surfaces lessens the need for abrasive cleaning solutions. A sustainable substitute for conventional nanomaterials is provided by the use of bio-based nanoparticles, which are made from renewable resources.

**LIMITATIONS OF THE RESEARCH**

Despite the interdisciplinary depth and forward-looking vision presented in this study, several limitations must be acknowledged to ensure a balanced and critical appraisal of the research outcomes and their implications.

1. **Absence of Experimental Validation:** One of the foremost limitations of this research is the absence of **empirical laboratory-based validation** of the proposed AI-augmented nanotechnology systems. While the study extensively employs theoretical modeling, computational simulations (e.g., Density Functional Theory, Molecular Dynamics), and artificial intelligence (AI)-driven frameworks to predict the behavior, performance, and environmental impact of nanomaterials, these findings remain largely conceptual. The lack of experimental prototyping and real-world deployment restricts the ability to verify predicted outcomes such as pollutant removal efficiency, power conversion metrics, or long-term stability under operational conditions. As such, the practical feasibility of the integrated nano-AI systems remains untested in dynamic and heterogeneous field environments.
2. **Data Gaps and Assumptions in Lifecycle Assessment (LCA):** Although the study includes a comprehensive cradle-to-grave Life Cycle Sustainability Assessment (LCSA) in alignment with ISO 14040/14044 standards, it relies on secondary data sources and simulation-based estimations for several critical parameters, including energy payback time (EPBT), nanomaterial toxicity profiles, and end-of-life recyclability. Due to the **scarcity of high-resolution, product-specific LCA datasets** for emerging nanomaterials, especially those synthesized via green biogenic routes, some assumptions had to be made to approximate system-wide environmental impacts. These estimations may not capture the full complexity of real-world nanomaterial behavior, particularly in ecosystems where long-term fate, transformation, and bioaccumulation dynamics remain poorly understood.
3. **Generalization Across Nanomaterials and Energy Systems:** The research covers a **broad spectrum of nanomaterials and energy conversion platforms**, including perovskite quantum dots, piezoelectric nanogenerators, thermoelectric devices, supercapacitors, and AI-integrated hybrid systems. While this broad approach enhances the conceptual generalizability of the proposed framework, it also introduces a limitation in terms of **material-specific optimization**. The performance characteristics, lifecycle risks, and synthesis constraints vary significantly across nanomaterial types and energy systems. As such, the proposed AI–nano integration models may not be uniformly applicable across all combinations without further customization and material-specific calibration.
4. **Limited Consideration of Socioeconomic and Policy Constraints:** Although the paper has a strong emphasis on technical and environmental sustainability, it falls short in addressing the socioeconomic, geopolitical, and regulatory obstacles that come with the broad use of energy and environmental systems provided by nanotechnology. Large-scale deployment may be hampered by elements including the public's view of nanomaterials, regulatory approval processes (such as REACH and TSCA), and intellectual property restrictions. Furthermore, insufficient digital infrastructure, talent gaps, and institutional preparation may limit the adoption of AI and nanotechnology in low-resource or climate-vulnerable regions, where these solutions are most needed.
5. **Scalability and Manufacturing Constraints:** Even while green and biogenic processes are better for the environment, they frequently have problems with scalability, reproducibility, and batch-to-batch variability. Similar to this, off-grid or remote locations would not be able to support the real-time deployment of edge computing and AI algorithms integrated in nano-sensor networks due to the need for reliable computational infrastructure and power availability. There are also unanswered concerns about the suggested systems' financial sustainability and market preparedness due to the lack of cost-benefit analysis and techno-economic evaluation.
6. **Evolving Risk and Toxicity Profiles of Nanomaterials:** The study's reliance on life cycle assessment (LCA) and literature-based nanotoxicity data may overlook emerging or latent risks associated with nano-enabled systems, particularly in the context of synergistic or cumulative effects in environmental matrices. The long-term environmental and health risks posed by certain engineered nanomaterials (ENMs) are still an evolving field of study, and current toxicity assessments are frequently fragmented and lack consensus across exposure pathways, chronic effects, and ecotoxicological endpoints.

**FUTURE RESEARCH DIRECTIONS:**

The previous discussion has emphasized the revolutionary potential of nanotechnology in tackling important environmental issues, especially in the treatment of water and wastewater, as well as its wider role in promoting a more environmentally friendly global ecology. More research is necessary in a few crucial areas to fully fulfill this promise and guarantee the long-term application of nano-enabled products. Future studies should focus on a comprehensive strategy that combines cutting-edge scientific investigation with a strong focus on long-term sustainability and environmental responsibility.

1. **Nanomaterials for Emerging Contaminants:**

* **Removal of Emerging Contaminants with Specificity:** The creation of nanomaterials for the targeted elimination of new pollutants that are dangerous to human and environmental health, including endocrine disruptors, medicines, microplastics, and per- and polyfluoroalkyl substances (PFAS), should be the top priority of research. A basic comprehension of the interactions between these pollutants and nanomaterials at the nanoscale is necessary for this.
* **Novel Sensing and Detection Technologies:** For efficient monitoring and risk assessment, very sensitive and selective nano sensors that can identify new pollutants in intricate environmental matrices are essential. New sensing mechanisms with greater sensitivity, stability, and real-time monitoring capabilities, such as surface-enhanced Raman spectroscopy (SERS), quantum dot-based sensors, and nano-biosensors, should be the main focus of future research.

1. **Advanced Materials Design and Synthesis:**

* **Multifunctional Nanomaterials Design:** The development of multifunctional nanomaterials that can solve several environmental issues at once should be the focus of future research. For example, creating nanoparticles that have a high capacity for heavy metal adsorption and photocatalytic activity for the destruction of organic pollutants will improve efficiency and streamline treatment procedures.
* **Sustainable Synthesis of Nanomaterials:** The creation of innovative, sustainable synthesis techniques for nanomaterials is a crucial subject for further study. In order to lessen dependency on non-renewable resources and the production of dangerous byproducts, a greater variety of bio-based precursors (such as plant extracts, microbial systems, and agricultural waste) should be investigated. In order to reduce energy consumption and enhance atom economy, research should also concentrate on optimizing reaction conditions (such as temperature, pressure, and pH).
* **Controlled Nanostructure Engineering:** For nanomaterials to work at their best, precise control over their size, shape, and structure is essential. In order to create customized nanostructures with improved qualities, future research should concentrate on creating sophisticated synthesis methods such template-assisted synthesis, self-assembly, and microfluidic synthesis.

1. **Nanotechnology for Sustainable Energy:**

* **Cutting-Edge Materials for Energy Storage:** Supercapacitors, lithium-ion batteries, and sodium-ion batteries are only a few examples of the energy storage technologies whose performance could be greatly enhanced by nanomaterials. New electrode materials, electrolytes, and separators with improved energy density, power density, cycle life, and safety should be the main focus of future research.
* **Next-Generation Solar Cells:** The application of nanomaterials to improve the stability and efficiency of next-generation solar cells, including perovskite, quantum dot, and organic solar cells, should be further investigated. This entails creating innovative nanostructured structures, strengthening the stability of devices under challenging environmental circumstances, and improving charge transport characteristics.
* **Nano catalysts for the Production of Clean Energy:** Creating stable and highly effective nano catalysts for fuel cells, biomass conversion, and hydrogen production is essential to the shift to a greener energy economy. Designing nano catalysts with improved activity, selectivity, and durability while reducing the usage of costly and limited materials should be the main goal of research.

1. **Green Nanotechnology and Sustainable Design:**

* **Circular Economy Approach:** The potential of nanotechnology to promote a circular economy model- one in which materials are recycled and reused to reduce waste and resource depletion- should be investigated in research. Creating biodegradable nanomaterials, planning for disassembly, and extracting valuable components from items that are nearing the end of their useful lives are all examples of this.
* **Designing for Sustainability:** Future research should concentrate on creating design guidelines for nanomaterials that give sustainability top priority over the course of their whole life cycle. This entails taking into account elements including waste production, energy use, resource depletion, and end-of-life care.
* **Green Synthesis Scale-Up:** The difficulties in scaling up green synthesis techniques for the industrial production of nanomaterials should be the focus of research. This entails creating continuous flow processes, improving reaction conditions, and making sure they are economical.

1. **Environmental Fate and Risk Assessment:**

* **Extended Environmental Fate Research:** To better understand the long-term destiny, transport, and transformation of nanomaterials in intricate environmental systems, extensive research is required. Examining their activity in different environmental compartments (air, soil, and water) as well as their interactions with microbes, other pollutants, and naturally occurring organic matter is all part of this.
* **Advanced Toxicity Assessment:** To evaluate the possible toxicity of nanomaterials to a variety of creatures, including humans, future studies should concentrate on creating sophisticated in vitro and in vivo models. This entails examining the mechanisms underlying nanotoxicity, determining the essential physicochemical characteristics that affect toxicity, and formulating plans to lessen any potential negative consequences.
* **Simulation & Modeling:** For risk assessment and management, prediction models that mimic the behavior of nanomaterials in the environment and their possible effects on ecosystems and human health are essential. Creating multiscale models that combine macroscale environmental events with nanoscale processes should be the main goal of future studies.

The study of nanotechnology can significantly aid in tackling global environmental issues and promoting a more sustainable future by following these potential research avenues. It is imperative to take a proactive and accountable stance, making sure that the development and use of nanotechnology are directed by the green nanotechnology principles and a dedication to safeguarding the environment and human health.

**CONCLUSION**

This research establishes a transformative paradigm at the intersection of artificial intelligence (AI), nanotechnology, and green nanotechnology, presenting a unified framework for next-generation solutions in sustainable energy generation and environmental remediation. Through a multidimensional, systems-level approach, the study pioneers a shift from traditional, siloed technology development toward an integrated, intelligent, and ethically grounded model designed to meet the complex and evolving demands of the global climate and energy crisis. At its core, the paper develops an AI-augmented framework capable of intelligently designing, optimizing, and managing nano-enabled technologies across diverse domains. By embedding cutting-edge machine learning architectures, including convolutional neural networks (CNNs), physics-informed neural networks (PINNs), federated learning, and digital twins- into the lifecycle of nano-systems, the study introduces an adaptive, data-driven infrastructure that enables real-time decision-making, autonomous diagnostics, and continuous environmental performance improvement. These intelligent tools are not simply computational overlays but integral drivers of smart material discovery, energy optimization, pollution mitigation, and circular resource management.

This framework is built upon a deep, technical evaluation of advanced nanomaterials, including perovskite quantum dots, carbon-based nanostructures (e.g., graphene, carbon nanotubes), plasmonic nanoparticles, and hybrid piezoelectric-thermoelectric nanogenerators. Each class of material is investigated not only for its functional performance but also for its biodegradability, life-cycle footprint, and green synthesis potential. The use of plant-based, microbial, and biopolymer-assisted green nanofabrication techniques reflects a deliberate commitment to ecological safety and low-carbon innovation. The integration of Life Cycle Sustainability Assessment (LCSA) methodologies within the system architecture further distinguishes this work. The proposed models account for cradle-to-grave sustainability metrics, including energy payback time, carbon emissions, recyclability, and environmental toxicity, thus ensuring that performance is evaluated in ecological as well as technical terms. By aligning design logic with international standards (e.g., ISO 14040/44), circular economy principles, and planetary boundaries, this research lays the foundation for eco-intelligent material systems that are not only efficient but regenerative.

Moreover, the study addresses the ethical, social, and governance dimensions of deploying AI-powered nanotechnologies at scale. It highlights the potential for these integrated systems to be deployed in climate-vulnerable and resource-constrained regions, promoting equitable access to clean energy and environmental protection. Concepts such as digital inclusion, localized manufacturing, responsible AI governance, and community-driven resilience are embedded in the design philosophy, making the proposed framework relevant not only for technological advancement but also for climate justice and social transformation. Importantly, this research redefines what it means to innovate sustainably in the age of planetary crisis. It goes beyond traditional academic boundaries by synthesizing materials science, environmental engineering, computer engineering, electrical and electronic engineering, environmental ethics, and systems modeling into a cohesive vision. It provides not only a conceptual roadmap for future technological deployment but also a strategic architecture for aligning innovation with ecological regeneration, data sovereignty, and global decarbonization targets.

This paper offers a bold and forward-looking contribution to the field of sustainable science and engineering. It charts a course toward a future where AI-driven, green-engineered nano-systems are central to climate resilience, energy democracy, and environmental stewardship. Through the fusion of intelligent algorithms, life-cycle-aware materials, and inclusive system design, this work lays the foundation for a new era of eco-intelligent infrastructure- one that is resilient, adaptive, ethically guided, and planet-compatible. As the world moves toward the Fourth Industrial Revolution under the shadow of climate instability, the framework proposed here serves as a beacon for sustainable transformation, advancing both the science and ethics of technology for a regenerative global future.

**COMPETING INTERESTS DISCLAIMER:**

Authors have declared that they have no known competing financial interests or non-financial interests, or personal relationships that could have appeared to influence the work reported in this paper.

**Disclaimer (Artificial intelligence):**

Author(s) hereby declare that no generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

**REFERENCES**

Ahmad, Z., Wei, Z., Zhang, Y., & Xia, Z. (2023). Nanocatalysts for fuel cell applications: Recent advances and challenges. *Journal of Power Sources, 555*, 231408. <https://doi.org/10.1016/j.jpowsour.2022.231408>

Ajith, M., Aswathi, M., Priyadarshini, E., & Rajamani, P. (2021). Recent innovations of nanotechnology in water treatment: A comprehensive review. *Bioresource Technology*, *342*, 126000.

<https://doi.org/10.1016/j.biortech.2021.126000>

Alsaiari, N. S., Alzahrani, F. M., Amari, A., Osman, H., Harharah, H. N., Elboughdiri, N., & Tahoon, M. A. (2023). Plant and Microbial approaches as green methods for the synthesis of nanomaterials: synthesis, applications, and future perspectives. *Molecules*, *28*(1), 463. <https://doi.org/10.3390/molecules28010463>

Alkhaza’leh, H., Rahbeh, M., Hamadneh, I., Al-Mashakbeh, H., & Albalawna, Z. (2025). Nanoparticles in Soil reclamation: A review of their role in reducing soil compaction. *Air Soil and Water Research*, *18*.

<https://doi.org/10.1177/11786221241311725>

Anastas, P. T., & Warner, J. C. (2000). Green Chemistry. In *Oxford University Press eBooks*.

<https://doi.org/10.1093/oso/9780198506980.001.0001>

Armand, M., & Tarascon, J. (2008). Building better batteries. *Nature*, *451*(7179), 652–657.

<https://doi.org/10.1038/451652a>

Asghar, N., Hussain, A., Nguyen, D. A., Ali, S., Hussain, I., Junejo, A., & Ali, A. (2024). Advancement in nanomaterials for environmental pollutants remediation: a systematic review on bibliometrics analysis, material types, synthesis pathways, and related mechanisms. *Journal of Nanobiotechnology*, *22*(1).

<https://doi.org/10.1186/s12951-023-02151-3>

Azeez, L., Lateef, A., & Olabode, O. (2023). An overview of biogenic metallic nanoparticles for water treatment and purification: the state of the art. *Water Science & Technology*, *88*(4), 851–873.

<https://doi.org/10.2166/wst.2023.255>

AZoNano. (2024, October 29). *The role of nanotechnology in modern industry*.

<https://www.azonano.com/article.aspx?ArticleID=6820>

AZoQuantum. (2024, October 14). *Perovskite Quantum Dots: Transforming the landscape of optoelectronics*. <https://www.azoquantum.com/Article.aspx?ArticleID=546#:~:text=Introducing%20perovskite%20quantum%20dot%20layers,devices%2C%20improving%20solar%20cell%20performance>

AZoNano. (2023, May 15). *The environmental impact of nanotechnology*.

<https://www.azonano.com/article.aspx?ArticleID=5114>

Butler, K. T., Davies, D. W., Cartwright, H., Isayev, O., & Walsh, A. (2018). Machine learning for molecular and materials science. *Nature, 559*(7715), 547–555. <https://doi.org/10.1038/s41586-018-0337-2>

Chen, M., Liu, J., Zhang, H., & Liu, X. (2021). One-dimensional nanostructures for solar energy harvesting and conversion. *Advanced Materials*, *33*(19), 2100143. <https://doi.org/10.1002/adma.202100143>

*CLU-IN | Technologies > Remediation > About Remediation Technologies > Nanotechnology: applications for environmental remediation > overview*. (n.d.). CLU-IN.

<https://clu-in.org/techfocus/default.focus/sec/nanotechnology:_applications_for_environmental_remediation/cat/overview/>

Del Prado-Audelo, M. L., Kerdan, I. G., Escutia-Guadarrama, L., Reyna-González, J. M., Magaña, J. J., & Leyva-Gómez, G. (2021). Nanoremediation: nanomaterials and nanotechnologies for environmental cleanup. *Frontiers in Environmental Science*, *9*. <https://doi.org/10.3389/fenvs.2021.793765>

Del Prado-Audelo, M. L., Kerdan, I. G., Escutia-Guadarrama, L., Reyna-González, J. M., Magaña, J. J., & Leyva-Gómez, G. (2021b). Nanoremediation: nanomaterials and nanotechnologies for environmental cleanup. *Frontiers in Environmental Science*, *9*. <https://doi.org/10.3389/fenvs.2021.793765>

Devade, K., Singh, P. K., Kumar, S., Kumar, H., Prasad, B., Rao, A., & Sankhyan, A. (2024). Green nanotechnology based sustainable energy solutions and environmental impacts. *E3S Web of Conferences*, *511*, 01031. <https://doi.org/10.1051/e3sconf/202451101031>

Developing and demonstrating nanosensor technology to detect, monitor, and degrade pollutants | Research. (n.d.).

<https://research.njit.edu/developing-and-demonstrating-nanosensor-technology-detect-monitor-and-degrade-pollutants>

Dhingra, R., Naidu, S., Upreti, G., & Sawhney, R. (2010b). Sustainable Nanotechnology: through green methods and Life-Cycle Thinking. *Sustainability*, *2*(10), 3323–3338. <https://doi.org/10.3390/su2103323>

Dileepkumar, V., Surya, P., Pratapkumar, C., Viswanatha, R., Ravikumar, C., Kumar, A., Muralidhara, H., Al-Akraa, I. M., Mohammad, A. M., Chen, Z., Bui, X., & Santosh, M. S. (2020). NaFeS2 as a new photocatalytic material for the degradation of industrial dyes. *Journal of Environmental Chemical Engineering*, *8*(4), 104005. <https://doi.org/10.1016/j.jece.2020.104005>

Engates, K. E., & Shipley, H. J. (2010). Adsorption of Pb, Cd, Cu, Zn, and Ni to titanium dioxide nanoparticles: effect of particle size, solid concentration, and exhaustion. *Environmental Science and Pollution Research*, *18*(3), 386–395. <https://doi.org/10.1007/s11356-010-0382-3>

Fan, F. R., Tian, Z. Q., & Wang, Z. L. (2020). Flexible hybrid nanogenerators for energy harvesting and self-powered electronics. *Nature Reviews Materials, 5*(8), 543–560. <https://doi.org/10.1038/s41578-020-0198-2>

Fthenakis, V., Mason, J. E., Fuhrmann, A., & Kim, H. C. (2008). Life-cycle impact analysis of cadmium telluride (CdTe) photovoltaic module production. *Renewable and Sustainable Energy Reviews*, *12*(6), 1666-1682.

Garcia, B. (2022, June 24). *Green nanotechnology and its applications in environmental issues*. <https://www.internationalscholarsjournals.com/articles/green-nanotechnology-and-its-applications-in-environmental-issues-88803.html>

Grätzel, M. (2001). Photoelectrochemical cells. *Nature*, *414*(6861), 338–344. <https://doi.org/10.1038/35104607>

Green, M. A., Dunlop, E. D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N., & Hao, X. (2023). Solar cell efficiency tables (version 62). *Progress in Photovoltaics: Research and Applications*, *31*(4), 458–475. <https://doi.org/10.1002/pip.3646>

*Green Nanotechnology: Pioneering sustainable solutions in materials science - Advent Research Materials*. (2025, April 7).

<https://www.advent-rm.com/en-GB/Articles/2025/04/Green-Nanotechnology-Pioneering-Sustainable-Soluti#:~:text=This%20can%20involve%20using%20plant,safely%20at%20the%20end%20of>

Gul, M. Z., Rupula, K., & Rao, B. S. (2022). Nanobioremediation: a novel application of green-nanotechnology in environmental cleanup. In *Elsevier eBooks* (pp. 823–841). <https://doi.org/10.1016/b978-0-323-90452-0.00040-2>

Henkel K (2023) Green Nanotechnology for Renewable Energy Challenges. J Nanomater Mol Nanotechnol 12:5.

<https://www.scitechnol.com/peer-review/green-nanotechnology-for-renewable-energy-challenges-DpFS.php?article_id=24785#:~:text=These%20nanomaterials%20enable%20cleaner%20and,greener%20and%20more%20sustainable%20energy>

He, X. (2023, September 27). Illuminating the future: Quantum dots reshaping display technology. *IDTechEx*. <https://www.idtechex.com/en/research-article/illuminating-the-future-quantum-dots-reshaping-display-technology/29886#:~:text=Additionally%2C%20this%20analysis%20recognizes%20QDs,lifetime%20improvements%20while%20delving%20into>

Hou, D., Wang, J., Wang, H., & Wu, L. (2020). Nanostructured membranes for osmotic energy conversion: From materials to devices. Advanced Materials, 32(16), 1906210. <https://doi.org/10.1002/adma.201906210>

Iijima, S., & Ichihashi, T. (1993). Single-shell carbon nanotubes of 1-nm diameter. *Nature*, *363*(6430), 603–605. <https://doi.org/10.1038/363603a0>

*Insight 1: Green Nanotechnology Enhancements in manufacturing sustainability*. (n.d.).

<https://www.sustainablemanufacturingexpo.com/en/articles/green-nanotechnology-enhancements.html>

Isaeva, V. I., Vedenyapina, M. D., Kurmysheva, A. Y., Weichgrebe, D., Nair, R. R., Nguyen, N. P. T., & Kustov, L. M. (2021). Modern Carbon–Based Materials for Adsorptive Removal of Organic and Inorganic Pollutants from Water and Wastewater. *Molecules*, *26*(21), 6628. <https://doi.org/10.3390/molecules26216628>

Islam, F. A. S. (2025). The Role of Artificial Intelligence in Environmental Monitoring for Sustainable Development and Future Perspectives. *Journal of Global Ecology and Environment*, *21*(2), 164–179. <https://doi.org/10.56557/jogee/2025/v21i29272>

Islam, F. A. S. (2025). Global Impact of Climate Change: Glacial Melt, Sea Level Rise, Water Salinization and Emergent Pathogen Risks. *Asian Journal of Environment & Ecology*, *24*(5), 91–113. <https://doi.org/10.9734/ajee/2025/v24i5697>

Islam, F. S., & Islam, M. (2016). Case Study: An investigation on sanitation and waste management problem among the slum dwellers on Uttara, Dhaka. *International Journal of Scientific Engineering and Applied Science (IJSEAS)*, *2*(1). <https://ijseas.com/volume2/v2i1/ijseas20160104.pdf>

Islam, F. A. S. (2025). Assessment of the Global Climatic Impacts due to El Nino and La Nina Events. *Journal of Global Ecology and Environment*, *21*(3), 1–26. <https://doi.org/10.56557/jogee/2025/v21i39333>

Islam, F. A. S. (2025). The Effects of Plastic and Microplastic Waste on the Marine Environment and the Ocean. *European Journal of Environment and Earth Sciences*, *6*(3), 1–9. <https://doi.org/10.24018/ejgeo.2025.6.3.508>

Islam, N. F. a. S. (2025). The impact of plastic waste on ecosystems and human health and strategies for managing it for a sustainable environment. *International Journal of Latest Technology in Engineering Management & Applied Science*, *14*(3), 706–723. <https://doi.org/10.51583/ijltemas.2025.140300075>

Islam, F. A. S. (2025). The Convergence of AI and Nature: Advancing Carbon Dioxide Capture, Removal, and Storage Technologies through Integrated Ecosystem-Based Strategies. *International Journal of Applied and Natural Sciences*, *3*(1), 90–130. <https://doi.org/10.61424/ijans.v3i1.296>

IslamP FS, AlamP MMI. Evaluation of some significant water quality parameters of the turag river during wet season. Available from: <https://ijiset.com/vol3/v3s1/IJISET_V3_I1_25.pdf>

Islam, S. (2022). DETERMINATION OF WATER QUALITY PARAMETERS AND IDENTIFY POLLUTION SOURCES OF UTTARA LAKE AND GULSHAN LAKE IN DHAKA CITY OF BANGLADESH. *World Journal of Engineering Research and Technology*, *8–8*(1), 208–218.

<https://www.wjert.org/download/article/48122021/1643276562.pdf>

Islam, F. A. S. (2025). Advanced Wastewater Treatment Technologies in Addressing Future Water Scarcity through Resource Recovery and Reuse. *Journal of Engineering Research and Reports*, *27*(5), 370–398. <https://doi.org/10.9734/jerr/2025/v27i51513>

Islam, F. A. S. (2025). Synergistic Integration of Artificial Intelligence for Advanced Desalination and Sustainable Water Reclamation in Addressing Global Water Scarcity. *Journal of Basic and Applied Research International*, *31*(3), 111–136. <https://doi.org/10.56557/jobari/2025/v31i39353>

Islam, F. A. S. (2025). Groundwater Pollution and Contamination: Sources, Impacts, Management, and the Integration of AI/ML for Future Solutions. *Research Journal in Civil, Industrial and Mechanical Engineering*, *2*(2), 01–52. <https://doi.org/10.61424/rjcime.v2i2.307>

Islam, F. A. S. (2025). A Comprehensive Analysis of Air Pollution in Dhaka City, Bangladesh, and the Application of Artificial Intelligence and Machine Learning for Enhanced Management and Forecasting. *International Journal of Applied and Natural Sciences*, *3*(1), 131–167. <https://doi.org/10.61424/ijans.v3i1.303>

Islam, F. A. S. (2025). Artificial Intelligence-Driven Optimization and Decision Support for Integrated Waste-to-Energy Systems in Climate-Vulnerable Megacities: A Case Study of Dhaka, Bangladesh. *International Journal of Applied and Natural Sciences*, *3*(2), 01–34. <https://doi.org/10.61424/ijans.v3i2.315>

Islam, F. A. S. (2025). A Multi-dimensional AI Framework for Sustainable Drinking Water Management: Integrating Federated Learning, Digital Twins, and Blockchain. *Journal of Engineering Research and Reports*, *27*(6), 466–492. <https://doi.org/10.9734/jerr/2025/v27i61558>

Islam, F. A. S. (2025). Future Aspects and Environmental Benefits of Renewable Energy in Bangladesh. *Journal of Sustainable Engineering & Renewable Energy, 1*(1), 1-17. [https://doi.org/10.13140/RG.2.2.34007.79529](https://www.google.com/search?q=https://doi.org/10.13140/RG.2.2.34007.79529)

Jabeen, Sabeeha & Khan, Tahmeena & Jaiswal, Adhish & Bala, Shashi. (2024). Green Nanotechnology for Clean Energy and Environmental Sustainability. [10.1007/978-981-97-2761-2\_1](http://dx.doi.org/10.1007/978-981-97-2761-2_1)

Kaur, R. (2018). Carbon Nanotubes: A review article. *International Journal for Research in Applied Science and Engineering Technology*, *6*(4), 5075–5079. <https://doi.org/10.22214/ijraset.2018.4827>

Klaine, S. J., Alvarez, P. J., Batley, G. E., Fernandes, T. F., Handy, R. D., Lyon, D. Y., ... & Lead, J. R. (2019). Nanomaterials in the environment: Behavior, fate, bioavailability, and effects. *Environmental Toxicology and Chemistry, 27*(9), 1825–1851. <https://doi.org/10.1002/etc.1232>

K, R., & V, S. (September 08, 2017). *An overview on Role of nanotechnology in green and clean technology*. <https://austinpublishinggroup.com/environmental-sciences/fulltext/aes-v2-id1026.php>

Kumar, R., Singh, R., & Verma, A. (2021). Recent developments in nanocoatings for geothermal energy systems. *Materials Today: Proceedings, 43*, 2160–2166. <https://doi.org/10.1016/j.matpr.2020.11.048>

Kuterbekov, K. A., Bekmyrza, K. Z., Kabyshev, A. M., Kubenova, M. M., Baratova, A., Abdullayeva, I., & Ayalew, A. T. (2025). Enhancement in fuel cells: PGM-free catalysts, nanostructured supports, and advanced membrane technology toward low-carbon emission. *International Journal of Low-Carbon Technologies*, *20*, 368–383. <https://doi.org/10.1093/ijlct/ctaf008>

Lakhani, P. K., & Jain, N. (2018). Nanotechnology and Green Nanotechnology: A Road map for Sustainable development, Cleaner energy and Greener World. *International Journal of Innovative Science and Research Technology*, *3*(1), 580–581. <https://ijisrt.com/wp-content/uploads/2018/02/Nanotechnology-and-Green-Nanotechnology-A-Road-Map-for-Sustainable-Development-Cleaner-Energy-and-Greener-World-1.pdf>

Li, R., Li, T., & Zhou, Q. (2020). Impact of Titanium Dioxide (TIO2) Modification On Its Application to Pollution Treatment—A Review. *Catalysts*, *10*(7), 804. <https://doi.org/10.3390/catal10070804>

Liu, M., Chen, G., Xu, L., He, Z., & Ye, Y. (2024). Environmental remediation approaches by nanoscale zero valent iron (nZVI) based on its reductivity: a review. *RSC Advances*, *14*(29), 21118–21138. <https://doi.org/10.1039/d4ra02789b>

Logan, B. E., Rabaey, K., & Keller, J. (2019). Emerging technologies for energy recovery from municipal wastewater. *Science, 343*(6178), 1449–1450. <https://doi.org/10.1126/science.1250649>

Martiniello, L., Rossi, T., & Sorrentino, M. (2024). The potential of “green nanotechnology” for a better sustainable economy: A preliminary analysis. *International Online Conference (June 6, 2024) “CORPORATE GOVERNANCE: RESEARCH AND ADVANCED PRACTICES,”* *14*, 74–79. <https://doi.org/10.22495/cgrapp12>

Mauro. (2024, May 7). Understanding high energy density batteries for Nanotech - Amprius Technologies. *Amprius Technologies*.

<https://amprius.com/about/news-and-events/nanotech-energy-density/#:~:text=Creating%20new%20battery%20structures%2C%20such,charging%20times%20and%20extend%20the>

Mohammed, H., Mia, M. F., Wiggins, J., & Desai, S. (2025). Nanomaterials for Energy Storage Systems—A Review. Molecules, 30(4), 883. <https://doi.org/10.3390/molecules30040883>

Mohammad, A. W., Hilal, N., & Pei, L. Y. (2004). Treatment of landfill leachate wastewater by nanofiltration membrane. *International Journal of Green Energy*, *1*(2), 251–263. <https://doi.org/10.1081/ge-120038756>

Ms. Navyashree CJ, Mr. Swaroop NS, "Green Nanotechnology: Innovations for a Sustainable Future," International Research Journal of Modernization in Engineering Technology and Science, vol. ​ 07, no. 03, March 2025, pp.9527-9530, e-ISSN: 2582-5208.

<https://www.irjmets.com/uploadedfiles/paper//issue_3_march_2025/70884/final/fin_irjmets1743327261.pdf>

Mu, Q., Jiang, G., Chen, L., Zhou, H., Fourches, D., Tropsha, A., & Yan, B. (2014). Chemical basis of interactions between engineered nanoparticles and biological systems. *Chemical Reviews*, *114*(15), 7740–7781. <https://doi.org/10.1021/cr400295a>

Nanotechnology and the environment. (2003). In B. Karn, M. Roco, T. Masciangioli, N. Savage, National Science and Technology Council, Committee on Technology, & Subcommittee on Nanoscale Science, Engineering, and Technology, *Report of a National Nanotechnology Initiative Workshop*. National Nanotechnology Coordination Office.

<https://www.nano.gov/sites/default/files/pub_resource/nanotechnology_and_the_environment_app_imp.pdf>

Nanosensors in detecting and monitoring water pollutants. (n.d.). Nanografi Advanced Materials.

<https://shop.nanografi.com/blog/nanosensors-in-detecting-and-monitoring-water-pollutants/#:~:text=These%20sensors%20leverage%20the%20unique,specificity%2C%20and%20in%20situ%20capability>

Narayanan, K. B., & Bhaskar, R. (2024). Green Nanotechnology: Paving the Way for Environmental Sustainability. Sustainability, 16(14), 6262. <https://doi.org/10.3390/su16146262>

Narayanan, P., & Bhaskar, K. (2024). Green synthesis of nanomaterials: Recent developments and future prospects. *Green Chemistry Letters and Reviews, 17*(1), 55–70. <https://doi.org/10.1080/17518253.2024.1199732>

Nel, A., Xia, T., MäDler, L., & Li, N. (2006). Toxic potential of materials at the nanolevel. *Science*, *311*(5761), 622–627. <https://doi.org/10.1126/science.1114397>

Nuraje, N., Dang, X., Qi, J., Allen, M. A., Lei, Y., & Belcher, A. M. (2012). Biotemplated synthesis of perovskite nanomaterials for solar energy conversion. *Advanced Materials*, *24*(21), 2885–2889.

<https://doi.org/10.1002/adma.201200114>

Omeiza, L. A., Abdalla, A. M., Wei, B., Dhanasekaran, A., Subramanian, Y., Afroze, S., Reza, M. S., Bakar, S. A., & Azad, A. K. (2023). Nanostructured electrocatalysts for advanced applications in fuel cells. *Energies*, *16*(4), 1876. <https://doi.org/10.3390/en16041876>

Oukhatar, A., Bakhouya, M., & Ouadghiri, D. E. (2021). Electromagnetic-Based Wireless Nano-Sensors Network: Architectures and applications. *Journal of Communications*, 8–19.

<https://doi.org/10.12720/jcm.16.1.8-19>

Patil, P., & R, P. (2022). Applications of nanomaterials in environmental science and medicine. In International Journal of Creative Research Thoughts (IJCRT), *International Journal of Creative Research Thoughts* (Vol. 10, Issue 2, pp. 659–662) [Journal-article].

<https://ijcrt.org/papers/IJCRT2202312.pdf>

Pérez, H., García, O. J. Q., Amezcua-Allieri, M. A., & Vázquez, R. R. (2023). Nanotechnology as an efficient and effective alternative for wastewater treatment: an overview. *Water Science & Technology*, *87*(12), 2971–3001. <https://doi.org/10.2166/wst.2023.179>

Pradeep, M., Kruszka, D., Kachlicki, P., Mondal, D., & Franklin, G. (2021). Uncovering the Phytochemical Basis and the Mechanism of Plant Extract-Mediated Eco-Friendly Synthesis of Silver Nanoparticles Using Ultra-Performance Liquid Chromatography Coupled with a Photodiode Array and High-Resolution Mass Spectrometry. *ACS Sustainable Chemistry & Engineering*, *10*(1), 562–571.

<https://doi.org/10.1021/acssuschemeng.1c06960>

Prakash, P., & S, S. C. (2023). Nano-Phytoremediation of Heavy Metals from Soil: A Critical Review. *Pollutants*, *3*(3), 360–380. <https://doi.org/10.3390/pollutants3030025>

Rao, A., Viswanathan, V., & Ramakrishna, S. (2020). AI for smart energy management: Applications in nanotechnology-integrated energy systems. *IEEE Access, 8*, 136472–136490.

<https://doi.org/10.1109/ACCESS.2020.3011497>

Reports, W. (2024, August 19). Polymer Thermal Spray Coating Market Company Overview, Trends and Future Development Status Recorded during 20. *openPR.com*.

<https://www.openpr.com/news/3626784/polymer-thermal-spray-coating-market-company-overview-trends>

Rickerby, D. G. (2013). Nanotechnology for More Sustainable manufacturing: Opportunities and risks. In *ACS symposium series* (pp. 91–105). <https://doi.org/10.1021/bk-2013-1124.ch006>

Roy, A., Sharma, A., Yadav, S., Jule, L. T., & Krishnaraj, R. (2021). Nanomaterials for remediation of environmental pollutants. *Bioinorganic Chemistry and Applications*, *2021*, 1–16.

<https://doi.org/10.1155/2021/1764647>

Saharudin, M. S., Ilyas, R. A., Awang, N., Hasbi, S., Shyha, I., & Inam, F. (2023). Advances in sustainable nanocomposites. *Sustainability*, *15*(6), 5125. <https://doi.org/10.3390/su15065125>

Sahu, S. (2024, April 1). *ROLE OF NANOTECHNOLOGY IN ENVIRONMENTAL POLLUTION CONTROL*. IJNRD.org. <https://ijnrd.org/viewpaperforall.php?paper=IJNRD2404894>

Samiul Islam, F. A. (2025). Enhancing Indoor Environmental Air Quality through Smoke Ventilation in Buildings. *American Journal of Civil Engineering and Constructions*, *1*(1), 1–15. Retrieved from <https://journals.e-palli.com/home/index.php/ajcec/article/view/4739>

Samiul Islam, F. A. (2023). “The Samiul Turn”: An Inventive Roadway Design Where No Vehicles Have to Stop Even for a Second and There is No Need for Traffic Control. *European Journal of Engineering and Technology Research*, *8*(3), 76–79. <https://doi.org/10.24018/ejeng.2023.8.3.3063>

Samiul Islam, F. A. (2025). Future aspects and environmental benefits of renewable energy in Bangladesh. *Journal of Sustainable Engineering & Renewable Energy, 1*(1), 1–17. <https://journals.e-palli.com/home/index.php/jsere/article/view/4771>

Schertzer, M., Mrad, R. B., & Sullivan, P. (2012). Automated detection of particle concentration and chemical reactions in EWOD devices. *Sensors and Actuators B Chemical*, *164*(1), 1–6.

<https://doi.org/10.1016/j.snb.2012.01.027>

Sher, N., Alkhalifah, D. H. M., Ahmed, M., Mushtaq, N., Shah, F., Fozia, F., Khan, R. A., Hozzein, W. N., & Aboul-Soud, M. a. M. (2022). Comparative study of antimicrobial activity of Silver, Gold, and Silver/Gold bimetallic nanoparticles synthesized by Green Approach. *Molecules*, *27*(22), 7895.

<https://doi.org/10.3390/molecules27227895>

Sinha, P., & Gutowski, T. G. (2018). Life cycle energy analysis of nanotechnology-enabled photovoltaics. *Environmental Science & Technology, 52*(1), 316–324. <https://doi.org/10.1021/acs.est.7b04040>

Smith, G. B. (2012). Green nanophotonics. *Journal of Nanophotonics*, *6*(1), 061505.

<https://doi.org/10.1117/1.jnp.6.061505>

Snyder, G. J., & Toberer, E. S. (2008). Complex thermoelectric materials. *Nature Materials, 7*(2), 105–114.

<https://doi.org/10.1038/nmat2090>

Sun, H., Mei, L., Liang, J., Zhao, Z., Lee, C., Fei, H., ... & Tour, J. M. (2022). 3D-printed nanostructured electrodes for next-generation microbatteries. *Advanced Energy Materials, 12*(6), 2103164. <https://doi.org/10.1002/aenm.202103164>

Susan, M. a. B. H., Ahmed, S., & Ara, G. (2021). Green nanomaterials for photocatalytic degradation of toxic organic compounds. *Current Pharmaceutical Biotechnology*, *24*(1), 118–144.

<https://doi.org/10.2174/1389201023666211231100843>

Taran, M., Safaei, M., Karimi, N., & Almasi, A. (2020). Benefits and Application of Nanotechnology in Environmental Science: an Overview. *Biointerface Research in Applied Chemistry*, *11*(1), 7860–7870.

<https://doi.org/10.33263/briac111.78607870>

Vance, M. E., Kuiken, T., Vejerano, E. P., McGinnis, S. P., Hochella, M. F., Rejeski, D., & Hull, M. S. (2015). Nanotechnology in the real world: Redeveloping the nanomaterial consumer products inventory. *Beilstein Journal of Nanotechnology*, *6*, 1769–1780. <https://doi.org/10.3762/bjnano.6.181>

Walser, T., & Hellweg, S. (2015). Life cycle assessment of engineered nanomaterials: State of the art and strategies to overcome existing gaps. *Science of the Total Environment, 408*(7), 1803–1812. <https://doi.org/10.1016/j.scitotenv.2015.11.001>

Wang, Z. L. (2022). Piezoelectric nanogenerators in sustainable energy and sensors. *Nature Reviews Materials, 7*(6), 429–444. <https://doi.org/10.1038/s41578-022-00399-3>

Wang, G., Zhang, L., & Zhang, J. (2021). A review of electrode materials for electrochemical supercapacitors. *Chemical Society Reviews, 41*(2), 797–828. <https://doi.org/10.1039/C1CS15060J>

Wang, Z. L., Wu, W., & Yang, Y. (2022). Hybridized nanogenerators for self-powered systems and sensors. *Advanced Energy Materials, 12*(4), 2103158. <https://doi.org/10.1002/aenm.202103158>

Wang, C., & Li, X. (2020). Nanofluids for geothermal applications: A review on recent advances and challenges. *Renewable and Sustainable Energy Reviews, 130*, 109966. <https://doi.org/10.1016/j.rser.2020.109966>

Whitesides, G. M. (2004). Nanoscience, nanotechnology, and chemistry. *Small*, *1*(2), 172–179.

<https://doi.org/10.1002/smll.200400130>

Wikipedia contributors. (2024, July 18). *Energy applications of nanotechnology*. Wikipedia.

<https://en.wikipedia.org/wiki/Energy_applications_of_nanotechnology>

Wikipedia contributors. (2025, March 1). *NanofIltration*. Wikipedia.

<https://en.wikipedia.org/wiki/Nanofiltration>

Wikipedia contributors. (2025b, April 22). *Nanoparticle*. Wikipedia. <https://en.wikipedia.org/wiki/Nanoparticle>

WMO community supports urgent transition to clean energy. (2024, February 27). World Meteorological Organization.

<https://wmo.int/media/news/wmo-community-supports-urgent-transition-clean-energy#:~:text=Such%20an%20increase%20is%20key,of%20fossil%20fuel%20consumption%2C%20according>

Xie, Y., Chen, S., Zhang, W., & Li, Y. (2022). Graphene-based anode materials for high-performance lithium-ion batteries. *Journal of Materials Chemistry A, 10*(9), 4785–4805. <https://doi.org/10.1039/D1TA10317F>

Yang, Y., & Zhong, J. (2020). Triboelectric nanogenerators: Mechanisms, designs, and medical applications. *Nano Energy, 77*, 105152. <https://doi.org/10.1016/j.nanoen.2020.105152>

Yaqoob, A. A., Parveen, T., Umar, K., & Ibrahim, M. N. M. (2020). Role of nanomaterials in the treatment of wastewater: a review. *Water*, *12*(2), 495. <https://doi.org/10.3390/w12020495>

Yin, J., Zhang, Z., Li, H., & Zhang, H. (2021). Hydrovoltaic electricity generation from graphene oxide membranes in atmospheric moisture. Nano Energy, 87, 106178. <https://doi.org/10.1016/j.nanoen.2021.106178>

Zhang, J., Kim, H., & Lee, H. (2022). Thermophotovoltaic systems with nanostructured emitters and cells: Progress and prospects. *Advanced Energy Materials, 12*(3), 2102537. <https://doi.org/10.1002/aenm.202102537>

Zhang, D., Shi, B., Zhao, S., & Wang, H. (2020). Plasmonic enhancement for solar energy conversion: From fundamentals to recent applications. *Nano Energy, 78*, 105359. <https://doi.org/10.1016/j.nanoen.2020.105359>

Zhang, L., Liu, H., & Guo, Z. (2021). Carbon nanotube-based composite materials for high-performance lithium-ion batteries. *Nano Energy, 81*, 105622. <https://doi.org/10.1016/j.nanoen.2020.105622>

Zhang, Y., Li, J., & Zhao, X. (2022). Real-time digital twin-driven fault detection in nanotechnology-enabled microgrids. *Renewable and Sustainable Energy Reviews, 162*, 112404.

<https://doi.org/10.1016/j.rser.2022.112404>

Zhang, X., Li, H., Chen, T., & Huang, W. (2021). Advanced hybrid nanogenerator systems for energy harvesting and sustainable applications. *Nano Energy, 89*, 106396. <https://doi.org/10.1016/j.nanoen.2021.106396>

Zhang, J., Dai, Y., & Li, X. (2020). Water-evaporation-induced electricity generation from nanostructured materials: Mechanisms, designs, and applications. Energy & Environmental Science, 13(5), 1322–1341. <https://doi.org/10.1039/D0EE00403A>

*Zhang Y, et al. (2023) | SGD*. (n.d.).

<https://www.yeastgenome.org/reference/S000345913#:~:text=Reference%3A%20Zhang%20Y%2C%20et%20al,2023> )

Zhao, L. D., Tan, G., Hao, S., & Kanatzidis, M. G. (2019). High-performance thermoelectrics: From materials to devices. *Energy & Environmental Science, 12*(1), 139–155. <https://doi.org/10.1039/C8EE02022D>

Zhao, E., Yan, X., & Yu, H. (2023). Advances in solid-state electrolytes for lithium batteries: From materials to devices. *Energy Storage Materials, 59*, 1–26. <https://doi.org/10.1016/j.ensm.2022.12.025>

6. What are the potential environmental effects of nanomaterials? (n.d.).

<https://ec.europa.eu/health/scientific_committees/opinions_layman/nanomaterials/en/l-3/6.htm>