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Advances in Nanomaterials and Green Chemistry for Sustainable Chemical Engineering: Applications in Environmental Remediation and Energy Storage

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ABSTRACT

Chemical engineering faces a growing need to balance the efficiency of the chemical industry with the need to reduce environmental pollution and resource depletion and to move toward low-carbon energy systems. Conventional treatment and energy-storage technologies are typically based on energy-intensive processes, limited raw materials, or toxic agents and products whose end-of-life effects are not well understood. The study critically explores the role of innovations in nanomaterials and green chemistry in more sustainable chemical engineering, focusing on environmental remediation and energy storage. The research design is qualitative, interpretivist, exploratory and documentary, and it examines peer-reviewed journal articles, review papers, scholarly books, institutional publications and policy literature that have been published primarily between 2020 and 2026, together with earlier seminal works. Secondary evidence was synthesized using qualitative thematic analysis, which allowed the identification of recurring scientific claims, technological pathways, limitations and research priorities. The results show that engineered nanomaterials such as metal and metal-oxide nanoparticles, carbon-based materials, nanocomposites, and biomass-derived composites are potential nanotechnological tools for adsorption, photocatalytic degradation, membrane separation, contaminant detection, and water, wastewater, air and soil remediation. Nanostructured electrodes, electrolytes, separators and interfacial materials are useful in energy storage to enhance the performance of batteries, supercapacitors and emerging energy storage devices. The review reveals that these advantages depend on green synthesis methods, responsible material design, scalable production, recyclability and thorough evaluation of nanomaterial toxicity and life cycle effects. The study makes the case for incorporating principles of sustainable innovation in research, development and deployment, including the integration of green chemistry principles, safe-and-sustainable-by-design approaches, resource efficiency and lifecycle thinking. The implications include the need for a more precautionary and systems-based approach to the development of environmental and energy technologies enabled by nanomaterials.

Introduction

Although industrialisation has been beneficial to the economy and society, it has also intensified environmental pressures associated with pollution, resource extraction, hazardous chemicals and the use of energy. Industrial sources such as chemical manufacturing, mining, textiles, electronics, agriculture and energy production generate complex effluents containing heavy metals, dyes, pharmaceuticals, pesticides, microplastics and other persistent contaminants. Traditional treatment technologies such as sedimentation, activated-sludge systems, chlorination and conventional adsorption can remove many pollutants, but some of these technologies use a lot of energy, generate secondary waste, or are not effective against emerging contaminants at low concentrations. As the world transitions to renewable electricity, energy-storage technologies need to become more efficient, durable and sustainable to address the intermittent nature of electricity generation and to electrify transportation and industry. Sustainable chemical engineering has emerged as an integrated approach that redesigns industrial systems and processes rather than simply treating industrial wastes.

The challenge of sustainable chemical engineering is to minimize environmental impacts of a chemical process without compromising technical efficiency, economics and social sustainability. It addresses resource efficiency, waste prevention, safer reagents/solvents, renewable feedstocks, energy economy, and process integration across the material's life cycle. In this context, environmental protection and industrial competitiveness are not mutually exclusive priorities; both should be taken into account at the very beginning of process design, and environmental impacts should be anticipated during raw material sourcing, manufacturing, use and end-of-life management. In nanotechnology, the same properties that make a material attractive for high performance may also make it difficult to characterize properly, difficult to recover and liable to be released into environmental systems.

Nanomaterials are proving to be important enablers of sustainable chemical engineering, since they have unique properties in the optical, electronic, catalytic, magnetic and adsorptive domains, which result from their small size and large surface-area-to-volume ratio. The catalytic, antimicrobial and remediation potential of metal nanoparticles such as silver, gold, copper and iron-based nanoparticles has been well studied. Metal-oxide nanomaterials of particular importance for photocatalysis, adsorption, sensing and electrochemical applications include TiO2, ZnO, Fe3O4, NiO and CeO2. Activated carbon nanostructures, graphene, graphene oxide, carbon nanotubes, fullerenes, and biomass-derived carbon offer high conductivity, tunable surface chemistry, mechanical stability and a large adsorption capacity. To address the drawbacks of individual constituents, these materials are combined in nanocomposites and hybrid structures. Porous and functionalized nanomaterials, such as surface-functionalized carbon structures and metal-organic frameworks, also offer controlled pore architecture and surface functional groups.

The usefulness of many materials depends on properties closely related to their composition and surface, such as surface area, porosity, conductivity, catalytic activity, surface functionalisation and stability. Tailored functional groups can enhance selectivity for specific pollutants or ions, and adsorption capacity and/or the number of active sites for catalytic reactions can be increased by high surface area. In energy-storage devices, nanostructuring can shorten ion and electron transport paths, accommodate volume changes during cycling and improve electrode–electrolyte contact. However, these benefits are not necessarily sustainable. Nanomaterial synthesis may require hazardous precursors, organic solvents, high temperatures, rare metals and high-energy processing methods. Thus, the environmental potential of nanomaterials should be assessed in conjunction with the manufacturing, application and disposal processes.

Green chemistry offers a response to these problems. The principles promote the prevention of waste, atom economy, the synthesis of less hazardous substances, the use of safer solvents and auxiliaries, energy efficiency, the use of renewable feedstocks, design for degradation, and the use of real-time analysis to prevent pollution. As far as nanotechnology is concerned, these principles have revived interest in the use of plant extracts, microbial systems, enzymes, biopolymers and other biological systems as reducing, stabilizing or capping agents. In addition, alternatives to conventional synthesis routes are being investigated, such as the use of water-based reaction systems, solvent-free processes, microwave-assisted and ultrasound-assisted synthesis, and lower-temperature processes. These approaches can decrease the consumption of hazardous reagents and energy and increase the use of renewable sources or waste materials.

However, caution should be exercised in using the term "green synthesis". A process that uses a plant extract but consumes large amounts of solvent, creates toxic by-products, uses non-renewable energy or wastes material is not sustainable. Similarly, biological reducing agents do not resolve questions about the toxicity, release, persistence and life-cycle burden of nanoparticles. True sustainability needs to be demonstrated with evidence of reagent source, process efficiency, waste generation, energy consumption, operator and environmental safety, scalability, and end-of-life. This is crucial because green chemistry can otherwise be used merely as a talking point instead of a genuine design concept.

Nanomaterials offer several promising avenues for environmental remediation. Heavy metals, dyes, nutrients and organic micropollutants can be removed from water by using adsorbents like graphene oxide, carbon nanotubes, metal-organic frameworks and functionalized nanoparticles. Under illumination, organic contaminants can be broken down with the aid of photocatalytic nanomaterials such as titanium dioxide, zinc oxide and composite semiconductors. Water purification and the detection and monitoring of contaminants could be further improved using nanomaterial-based membranes, sensors, and antimicrobial surfaces. These technologies are particularly pertinent for pharmaceutical residues, per- and polyfluoroalkyl substances, endocrine-disrupting chemicals and other emerging pollutants which are challenging to treat using conventional methods.

In practice, however, remediation applications face some important limitations. Adsorption performance is affected by pH, ionic strength, competing ions, pollutant concentration, contact time and matrix complexity. Photocatalytic systems also face several challenges, such as the requirement for UV light, fast electron–hole recombination, low visible-light activity or catalyst deactivation. The possibility of aggregation, leaching and particles that are hard to separate from treated water raises concerns about secondary pollution and ecological exposure. Hence, regeneration, reuse, material recovery and long-term stability are important issues to address for industrial implementation. Reviews identify not only contaminant-removal efficacy but also scalability, cost, durability, recovery and environmental risk as challenges for water-treatment nanomaterials.

Nanomaterials are also very important in sustainable energy storage. Although lithium-ion batteries remain the most popular choice for portable electronics and electric mobility, sodium-ion batteries are attracting interest because of the availability of sodium and its potential to be less costly than lithium. Nanostructured cathodes, anodes, electrolytes, separators and electrode interfaces can affect ion diffusion, electronic conductivity, ion storage capacity, cycling stability and safety. Carbon-based materials, silicon and metal-oxide nanostructures, layered oxides, Prussian-blue analogues and nanocomposite electrodes are being studied to enhance battery performance. High-surface-area carbon materials, conductive networks and hybrid nanostructures are also key to developing supercapacitors that store charge through electrochemical double-layer capacitance and fast surface redox reactions.

These developments support the integration of renewable energy resources and make energy-storage systems more flexible and responsive. However, the sustainability of energy storage cannot be assessed from electrochemical performance alone. Lithium, cobalt, nickel, graphite and other battery materials raise concerns about mining impacts, geographic concentration, supply security, recycling complexity and end-of-life waste. Although sodium-ion technologies might lessen the reliance on some critical materials, electrode durability, electrolyte chemistry, manufacturing readiness and the lifetime of sodium-ion batteries still need to be considered. This means that material substitution, efficient production, long service life, reparability, valuable substance recovery and recycling are imperative for a sustainable energy-storage transition.

Although research on nanomaterials has advanced through many scientific publications, the existing literature tends to separate the topics of nanomaterial innovation, green chemistry, environmental remediation and energy storage. Remediation studies may focus on pollutant-removal performance without considering synthesis impacts or release of nanomaterials. Energy-storage research, by contrast, may focus on capacity, rate capability and cycling stability while paying little attention to resource origin, toxicity, recyclability or industrial scale. Green-synthesis studies, meanwhile, may present environmentally desirable inputs but give limited life-cycle or safety information. This fragmentation makes it difficult for chemical engineers, policy makers and industry to determine whether a nanomaterial-based technology is truly sustainable across the entire system boundary.

To fill this gap, the present study uses a qualitative, interpretivist and exploratory analysis of secondary documentary scientific evidence. It critically examines the synergies and challenges of the evolving concepts of green chemistry and sustainable chemical engineering in the context of nanomaterials, focusing on the environmental remediation and energy storage field. The goal is not to present new experimental data but to collate, interpret and critically evaluate the available peer-reviewed and institutional evidence. The study aims to move beyond technological optimism and identify the conditions under which the innovation of nanomaterials could help make chemical-engineering systems safe, resource-efficient and circular.

The objectives of the research are to: (a) understand the connection between innovation of nanomaterials and sustainable chemical engineering; (b) examine the intersection of green chemistry with the development of environmentally friendly nanomaterials; (c) discuss the use of nanomaterials in environmental remediation and critically assess their use; (d) discuss the contribution of nanomaterials to sustainable technologies for storage of energy; and (e) understand the technological, environmental, economic and regulatory challenges of implementation. Four research questions are posed in the study:

1. How do innovations in nanomaterials fit into the context of sustainable chemical engineering applications (e.g., environmental remediation and energy storage)?

2. How can the principles of green chemistry help in the environmentally responsible synthesis, use, and management of nanomaterials?
3. What are the benefits, limitations and risks involved in using nanomaterials to clean water, treat wastewater, remove pollutants, and monitor the environment?
4. What are the technological, environmental, economic and regulatory issues for sustainable development and industrialization of energy-storage nanomaterials?

The study takes a critical documentary approach to answering these questions and thus adds an integrated sustainability perspective to nanomaterial and green-chemistry research. Its value lies in combining material innovation with life-cycle responsibility, environmental safety, resource efficiency and industrial feasibility, pointing towards more precautionary and systems-oriented solutions in sustainable chemical engineering.

Literature Review

Scientific principles and development of advanced nanomaterials

Advanced nanomaterials occupy a unique position in sustainable chemical engineering because their properties result from both chemical composition and nanoscale architecture. Materials at dimensions below about 100 nanometres can show increased surface area, changed electronic structure, increased catalytic activity, quantum confinement effects, and stronger interaction with light, ions and molecules. The properties of nanomaterials make them a subject of many investigations in the fields of adsorption, catalysis, sensing, membrane technology, and electrochemical energy storage. However, recent reviews have highlighted the need to consider the relationship between the structure of a nanomaterial and the function that it is designed to serve in a specific environment or energy application.

Metal and metal-oxide nanoparticles are among the most widely studied nanomaterials. Nanoparticles of silver, gold, copper and iron are highly desirable for catalytic, antimicrobial, redox and adsorption applications, and titanium dioxide, zinc oxide, iron oxide, nickel oxide and cerium oxide are well known for photocatalysis, contaminant removal, sensing, and battery applications. Metal-oxide semiconductors can create electron–hole pairs on illumination, which can be used for the degradation of organic pollutants; however, charge-carrier recombination, limited visible-light absorption in some materials, and photocorrosion or deactivation remain limitations. Composite semiconductor systems have therefore often been proposed to improve charge separation and widen light absorption.

Carbon-based nanomaterials offer a complementary platform for remediation and energy storage. Graphene and graphene oxide offer high theoretical surface area, electrical conductivity and chemical tunability, while carbon nanotubes provide conductive one-dimensional structures for electron transport and mechanical reinforcement. The production of carbon materials from biomass materials is of interest because of the potential to turn agricultural, forestry or municipal wastes into functional carbon adsorbents and electrode materials. Carbon-based nanomaterials have been reviewed for environmental remediation applications such as adsorption, photocatalysis and membrane integration; however, the performance of these materials is highly dependent on their precursor quality, activation method, surface chemistry and post-treatment conditions.

Nanocomposites and hybrid nanostructures are becoming increasingly important because they can combine the benefits of different components. For instance, a semiconductor material can be used in combination with a carbon material to enhance electron transfer and limit recombination, and magnetic materials can make it easier to recover the adsorbent after water treatment. Furthermore, functionalized nanomaterials can be designed to have carboxyl, amino, thiol or other surface groups to enhance the binding affinity for specific heavy-metal ions or organic contaminants. Surface engineering can increase selectivity, but it can also make synthesis more complex and expensive and add extra chemical inputs that can have environmental impacts.

Controllable pore size, high internal surface area and chemically adjustable binding sites are further opportunities provided by porous and functionalized materials such as metal-organic frameworks, covalent organic frameworks, and engineered porous carbons. They are modular and well suited to selective adsorption, catalysis, gas separation and electrochemical applications. The sustainability of these materials is not built in, however. Some frameworks rely on metal centres, petrochemical linkers or high-energy, solvent-

intensive activation processes. Their environmental value should therefore be assessed across synthesis, use and recovery, and not solely on adsorption capacity or electrochemical activity.

A common drawback in the nanomaterials literature is that laboratory performance is often reported, but durability, manufacturability and environmental release are not. Studies may show excellent uptake or good charge storage capacity in a controlled environment, but provide limited evidence of long-term stability, real-water matrices, regeneration cycles, and scale-up. This does not negate the scientific value of such studies, but their results should be understood as indications of potential, not as evidence of deployable sustainability.

Sustainable Nanomaterial Synthesis: Green Chemistry

Green chemistry provides a normative approach to mitigating the environmental impact of the production of nanomaterials. Its fundamentals include waste prevention, atom economy, less hazardous chemical syntheses, safer solvents and auxiliaries, energy efficiency, renewable feedstocks and design for degradation. When translated to the field of nanoscience, these principles promote process designs that use fewer and less dangerous reagents, conduct the process under milder conditions, use water and/or renewable solvents, and decrease energy consumption. Recent reviews have referred to green nanotechnology as an approach combining these with controlled fabrication of nanoscale materials.

Plant-derived synthesis has received special attention because plant extracts contain biomolecules that can act as reducing, capping and stabilizing agents. Other biological materials, such as microorganisms, enzymes, polysaccharides, etc., have also been employed for the synthesis of metal and metal-oxide nanoparticles. These methods can take place under comparatively mild temperature and pressure conditions, and may help to cut down the need for synthetic reducing agents. Simplicity, potential cost reduction and environmental compatibility are among the main motivations for the green synthesis of nanoparticles, as reported in reviews.

However, it should not be assumed that biological synthesis is necessarily better for the environment. Biomass cultivation, extraction, purification, and transport may lead to land, water and energy requirements. The benefits of using a plant extract might be offset by factors such as the amount of solvent used, downstream purification, yield of nanoparticles, repeatability and waste generation. Furthermore, a green precursor does not guarantee a green product: biological routes for the production of nanoparticles may result in nanoparticles with toxicity, persistence, or release issues. The literature therefore increasingly argues that evaluation should cover the entire life cycle of the process, not merely the fact that a reagent is “green”.

Another major trend is water-based or solvent-minimized systems. Water is usually very desirable when it can be safely handled and is compatible with the reaction chemistry. Solvent-free methods, mechanochemical approaches, microwave and ultrasound-assisted synthesis and electrochemical synthesis can also decrease solvent use or reaction time. However, these methods may come with other costs, such as high local energy consumption, special equipment requirements or difficulties in controlling particle size and shape. A defensible sustainability assessment will therefore require alternative routes to be compared using consistent system boundaries and appropriate environmental indicators.

In conventional nanomaterial synthesis, stoichiometric reagents, stabilizers, washing steps and solvent recovery are common, which makes atom economy and waste minimization particularly significant. Green chemistry promotes catalytic routes that increase the proportion of materials incorporated into products and eliminate or reduce waste. In industry, it also means paying attention to the yield of reaction, losses in purification, recycling of solvents, management of wastewater and recovery of unreacted materials.

The literature shows a critical debate on the state of maturity of green synthesis. In some studies, biological and low-impact approaches are considered near-term alternatives to conventional synthesis, while others emphasize that reproducibility, batch-to-batch consistency, scalable production and control of size and morphology are still to be solved. Both positions are correct to some extent: green synthesis is a viable approach for a large number of materials; however, the extent to which it may be applied at industrial scale depends on the material, the application, and the required quality. This variation highlights the importance of transparency in reporting synthesis conditions, yields, energy consumption, hazards of reagents, and waste streams.

Environmental Remediation with Nanomaterials

Nanotechnology for environmental remediation has grown at a rapid pace, because many pollutants are complex, present at low concentrations and persistent, which makes them difficult to remove using traditional treatment methods. For water and wastewater treatment, nanomaterials have been applied as adsorbents, photocatalysts, membrane modifiers, antimicrobial materials and sensing materials. They have a high surface area and tunable chemistry, which enables them to bind to heavy metals, dyes, pharmaceuticals, pesticides, pathogens and other pollutants. According to reviews, adsorption, photocatalytic degradation, membrane filtration and antimicrobial activity are among the most significant removal mechanisms achieved through nanostructured materials.

Heavy-metal remediation reflects both the promise and the challenge of using nanomaterials. The high adsorption capacity and tunable binding sites can be obtained by using graphene oxide, carbon nanotubes, metal-organic frameworks, and metal-oxide nanoparticles. Selectivity for specific toxic ions may be improved by surface functionalization with thiol, amino or carboxyl groups. Real wastewater, however, contains competing ions, natural organic matter, and variable pH that may affect the efficiency of adsorption and/or material stability. Also essential is the issue of regeneration: if an adsorbent is not regenerated efficiently, it can move the environmental issue from water contamination to solid-waste generation.

Photocatalysis is another important remediation mechanism. Under illumination, semiconductor nanomaterials like titanium dioxide (TiO2), zinc oxide (ZnO) and nickel oxide (NiO) can produce reactive species that can degrade organic contaminants. To enhance visible light response, charge separation and stability, composite photocatalysts are frequently designed. Photocatalysis is promising for dyes, pharmaceutical residues and other organic micropollutants; however, practical use is limited by the availability of light, the design of the reactor, the recovery of the catalyst, the turbidity of the water and the formation of transformation products. The literature therefore warns that degradation does not necessarily mean detoxification unless transformation products are identified and evaluated.

Nanomaterials' treatment power is especially challenged by emerging contaminants. Persistent organic pollutants, endocrine-disrupting chemicals, personal-care products and pharmaceutical residues may be present at low levels yet still cause public-health or ecological effects. Nanostructured adsorbents, photocatalysts, membranes and sensing platforms offer complementary approaches to these contaminants. However, they may not work well in complex municipal or industrial effluents compared to synthetic solutions in the laboratory. A key methodological challenge in the field is the discrepancy between controlled experiments and real-world conditions.

Industrial wastewater treatment introduces additional limitations, including high pollutant concentrations, changing composition, fouling, corrosion and the need for continuous operation. For nanomaterial-enabled membranes designed to increase selectivity and flux, membrane fouling, cleaning needs and nanoparticle leaching are practical concerns that should be investigated. Nanomaterial sensors can also be used to monitor contaminants in real time; however, their reliability depends on selectivity, calibration stability and compatibility with the harsh industrial environment. Integration into existing treatment infrastructure is as crucial as the intrinsic performance of the nanomaterial itself.

In remediation studies, four limitations repeatedly appear: real matrices are not fully evaluated, regeneration and reuse are not sufficiently considered, nanomaterial release is not well understood, and life-cycle evidence is limited. These limitations do not mean that the promise of nanomaterial remediation is void, but they show that high removal efficiency in the laboratory does not adequately represent sustainability. Long-term stability, material recovery, ecotoxicity, and compatibility with existing water-treatment systems should be considered more heavily in future research.

Because renewable electricity production is often intermittent and geographically distributed, energy storage is now an important part of sustainable chemical engineering. The presence of nanomaterials in energy storage devices has the potential to alter the architecture of the electrodes, ion transport, stability of the interface between the electrode and electrolyte, and conductivity of electrons within the device. Nanostructuring can shorten diffusion lengths, increase electroactive surface area, buffer volume changes during cycling and improve contact between the active materials and the conductive networks. This is why nanomaterials are extensively studied for lithium-ion batteries, sodium-ion batteries, supercapacitors and emerging storage technologies.

Nanomaterials are employed in the cathodes and anodes of lithium-ion batteries, as well as in the conductive additives, separators, and electrolyte interfaces. Conductive carbon-based materials like carbon nanotubes, graphene and others can enhance electron transfer, and nanostructured metal oxides or silicon-based materials can increase the theoretical capacity. However, nanoscale electrode materials could also promote undesired side reactions and make electrode processing more difficult. High performance must therefore be balanced with safety, stability, rate capability, capacity and manufacturability.

Sodium-ion batteries have attracted increasing interest as a potential alternative to lithium-ion batteries, especially in stationary storage applications. Sodium is available in greater supply and at lower cost than lithium, potentially alleviating supply chain stress and material costs. Recent reviews focus on advances in cathode and anode materials, electrolyte formulations, and understanding of sodium-ion diffusion mechanisms. However, sodium-ion technology faces challenges, such as lower energy density in some designs, electrode degradation, and the need to improve cycle life and commercial scalability. While nanomaterial engineering may help to address these limitations, it cannot resolve problems of resource use, manufacturing effects and recycling.

Supercapacitors offer high power density, fast charge/discharge rates and long cycle life, which make them ideal for short-term energy-buffering applications. Carbon-based nanomaterials are of particular interest because their high surface area makes them useful for

electric double-layer capacitance, while pseudocapacitive materials store charge through fast surface redox reactions. Hybrid supercapacitors combine battery-type and capacitor-type electrodes to achieve an optimal balance of energy and power. As with batteries, sustainability depends on more than the electrochemical behaviour of the cells; it also concerns the durability of the electrodes, the safety of the electrolyte, the sourcing of materials, and the recyclability of the cells.

It is now acknowledged in the literature that high-performing electrode materials are not the only requirement for sustainable storage of energy. The wider sustainability of lithium-ion and other battery systems is influenced by critical raw material dependence, the impact of mining, geographic concentration of supply and the complexity of recycling. Although sodium-ion technologies can decrease the need for some limited materials, this does not remove the importance of responsible sourcing, efficient manufacturing processes or end-of-life recovery. Life-cycle thinking therefore becomes essential for comparing storage technologies and preventing problems from being shifted from one environmental domain to another.

Another limitation is that many energy-storage studies test materials in the laboratory over short cycling regimes. Such studies may be useful for understanding mechanisms, but they may not reflect long-term degradation, manufacturing defects, thermal behaviour or performance in realistic operating environments. Moreover, there are no common sustainability metrics, which makes it difficult to compare studies with different electrode formulations, electrolytes, testing protocols or system boundaries. This methodological diversity weakens the inferences that can be drawn about the sustainability of nanomaterial-based storage.

Sustainability Challenges, Industrial Translation and Future Research

A key sustainability challenge is that nanomaterials may reduce environmental impacts at some points in a system while creating environmental risks at others. Because they are small, highly reactive and potentially mobile, they raise concerns about human exposure, environmental persistence, unintentional release during manufacturing, use, disposal and recycling, and resulting ecotoxicity. Research therefore indicates that functional performance can no longer be separated from hazard characterization, exposure assessment and safe-and-sustainable-by-design approaches to environmental health and safety.

A lifecycle approach is useful in considering these issues because it considers environmental impacts from raw-material extraction through production and use to end of life. Life-cycle assessment can highlight burdens from precursor production, solvent use, energy consumption, manufacturing yield, transport, regeneration and disposal for both adsorbent and energy-storage nanomaterials. However, life-cycle studies of nanomaterials remain limited because of insufficient inventory data, uncertainty about the environmental fate of nanomaterials and limited knowledge of their commercial-scale production. With these gaps, it is hard to consistently compare nanomaterial technologies to traditional technologies.

Other considerations in industrial translation include scalability, cost and process reliability. Laboratory synthesis can provide small quantities of well-characterized material, but commercial deployment requires materials that are of consistent quality, produced at high throughput, safe to handle, subject to quality control and compatible with existing equipment. Even if they are safer than traditional synthetic routes, green synthesis methods must also be reproducible, high-yielding, sufficiently fast and economically competitive. Scalability, cost, durability and material recovery are consistently mentioned as challenges to the practical use of water treatment and energy storage technologies that rely on nanomaterials.

One more question left unanswered is regulatory governance. Chemical regulations, which typically apply to bulk substances, may be inadequate for the effective control of nanomaterials, particularly when the size, coating or agglomeration changes the hazard profile of the nanomaterials. Responsible governance involves not only risk assessment after development but also forward thinking on safer material design, exposure prevention, worker protection, environmental monitoring and post-market surveillance. Incorporating green chemistry into regulatory and industrial decision-making is one way to shift the emphasis from end-of-pipe control towards prevention.

The concepts of circular economy offer a partial solution to these problems. Material recovery, adsorbent regeneration, battery recycling, reuse of carbon materials and design for disassembly are ways of reducing waste and recovering valuable materials. However, it is technically difficult to make circularity a reality for complex nanocomposites, embedded nanoparticles, contaminated adsorbents and multi-material battery cells. Recovery processes may also require energy or chemicals, so the benefits of circular strategies need to be demonstrated, not assumed.

Overall, the literature suggests that nanomaterials and green chemistry can play a crucial role in supporting sustainable chemical engineering, if they function successfully and safely, use resources efficiently, can be scaled up and are managed responsibly across their life cycles. The most salient unanswered questions are related to the standardisation of sustainability assessment, the proof of

safe and economical scalability, recovery of nanomaterials from complex environmental and energy systems, and the alignment of innovation with precautionary governance. These questions underpin the thematic findings and discussion in the following sections.

The results of this documentary study indicate that nanomaterials and green chemistry are redefining the potential of sustainable chemical engineering, but that technological capability alone is not enough to define sustainability. By exploiting the nanoscale structure of nanomaterials, which provides high surface area, tunable surface chemistry, enhanced conductivity, and multiple active sites, catalytic processes can be optimized, pollutants removed, and sensing and electrochemical energy storage enhanced. However, these same characteristics can increase environmental reactivity, make recovery more difficult and pose exposure risks. The main conclusion of the analysis is therefore that nanomaterial innovation has to be evaluated as a socio-technical and life-cycle system, not simply in terms of material performance.

Research Methodology

Research Design

The study uses a qualitative research design with an interpretivist, exploratory, documentary and secondary-evidence approach. It aims to discuss critically the role of nanotechnology and green chemistry in sustainable chemical engineering, focusing on environmental cleanup and energy storage. The research generates no primary data; instead, it interprets and synthesizes existing evidence from the scientific literature, including peer-reviewed journals, review papers, scientific books, institutional reports, regulatory reports and publications of recognized scientific organizations. A documentary approach is appropriate when the research questions concern the state, interpretation, limitations and implications of a large and growing scientific literature, rather than whether a particular material or process performs under a specific set of controlled conditions.

An exploratory orientation enables the study to uncover recurring patterns, unresolved tensions and new research priorities across multiple, inter-related fields. By analyzing these innovations in light of green synthesis, environmental remediation and electrochemical energy storage, a documentary synthesis can reveal relationships and gaps that might not be visible in a single discipline's literature. This design is also congruent with the goal of the study, which is the critical evaluation of sustainability claims. It helps the researcher to differentiate evidence-based conclusions from technological optimism, and preliminary laboratory results from "greenness" claims that are unsupported by life-cycle or safety analysis.

Research Philosophy

The study is based on the interpretivist research philosophy. Interpretivism rests on the premise that scientific knowledge is constructed and made sense of within particular social, institutional and disciplinary contexts. The documentary record in this study is therefore seen not as a dispassionate collection of facts, but as an expression of academic debates about technological opportunities, environmental risks, working methods and sustainability issues. This orientation is appropriate because technical, economic, environmental, resource-security, worker-safety and regulatory-preparedness issues are all considered important in debates on nanomaterials and green chemistry.

An interpretivist approach can also assist with the critical examination of how sustainability is defined and assessed. For example, a nanomaterial could be claimed to be environmentally friendly because it filters out contaminants or improves battery capacity, yet be produced with toxic chemicals, rare elements or energy-intensive processes. Interpretivism enables the study to address these multiple meanings and to ask what conditions, system boundaries and assumptions are needed for a technology to be deemed sustainable. The analysis therefore moves beyond description to interpreting the implications of the scientific claims recorded.

Sources of Secondary Evidence

The study uses several types of secondary documentary sources. The first type is peer-reviewed scientific journal articles, including original research, critical reviews, systematic reviews, and bibliometric or methodological reviews. The second type is scholarly books, book chapters and academic publications giving conceptual background in nanotechnology, green chemistry, environmental engineering and electrochemical energy storage. The third category comprises institutional and scientific reports from organizations concerned with chemical safety, environmental regulation and sustainable innovation.

Documents pertaining to regulation and standards are also included where relevant, to inform the analysis of nanomaterial safety, nanomaterials in the workplace, risk management and responsible innovation. These include publications and technical guidance from the Organisation for Economic Co-operation and Development (OECD) and the International Organization for Standardization (ISO). For instance, OECD publications describe safe-and-sustainable-by-design approaches and regulatory preparedness for nanomaterials and nano-enabled products and ISO guidance on occupational health and safety practices for manufactured nanomaterials.

Suitable scholarly sources include journals indexed in Scopus and Web of Science and published through ScienceDirect, SpringerLink, Wiley, ACS Publications and RSC Publishing. Institutional material may come from the OECD, ISO, the United Nations Environment Programme and other reputable scientific or environmental bodies. No formal database search with specified dates, keywords, numbers of searches or screening statistics was conducted. Instead, the documentary sources are published academic and institutional documents identified in line with the research aims.

Documents were assessed and selected as follows. Documents were considered relevant if they addressed one or more of the following principal aspects of the study: nanomaterial innovation, green synthesis, environmental remediation, energy storage, sustainability assessment, safety, regulation, and industrial implementation. Priority was given to literature published from 2020 to 2026, while seminal works that introduced key concepts, such as the principles of green chemistry and the thematic analysis method, were also included.

Each document was evaluated for topical relevance, scientific validity, publication quality, methodological transparency and value in answering the research questions. The clarity of the objectives, the appropriateness of research methods, the clarity of the reported results, and the degree to which the findings were supported by the results were evaluated with respect to the research objectives. Review articles were judged on the breadth and balance of their synthesis, their discussion of limitations and their identification of consensus and disagreement among primary studies.

Institutional and regulatory documents were not treated as peer-reviewed research. They were used mainly to provide background information on governance arrangements, safety principles, regulatory preparedness and policy recommendations, not to support claims about the scientific performance of particular materials. This distinction is important because evidence can be experimental or mechanistic, or it can be normative (institutional documents, risk-management frameworks, policy interpretations). Both types of evidence are useful, but they play different roles in the analysis.

Qualitative Thematic Analysis

Qualitative thematic analysis was used to analyse the secondary evidence, following the six-phase approach of Braun and Clarke (2006). Thematic analysis is appropriate for identifying patterns of meaning across varied textual evidence because it can be used to identify, organize, interpret and report meaning. Although the phases are listed in order, the analysis was iterative, with reading, coding, theme development and interpretation continuing across the stages.

In the first phase, the researcher read and re-read the articles, reviews, reports and standards pertinent to the study to become familiar with them. Analytical notes were used to document the main arguments, methods, findings, limitations and sustainability claims of all sources. In the second phase, initial codes capturing meaningful concepts were developed, such as “high surface area”, “photocatalytic degradation”, “green synthesis”, “nanoparticle toxicity”, “electrode stability”, “material recovery” and “safe-and-sustainable-by-design”.

In the third phase, related codes were grouped into initial themes. For instance, environmental remediation codes were grouped into one category and energy-storage codes into another to highlight the main target fields. In the fourth phase, the preliminary themes were examined to check that they were internally coherent and sufficiently distinct from each other in relation to the coded evidence and the entire documentary corpus.

In the fifth phase, the themes were refined and finalized. Each theme was clearly defined and linked to the research questions. Analytical synthesis and reporting formed the final phase, in which the results were integrated into five themes: functional innovation in nanomaterials; green chemistry as a basis for sustainable synthesis; environmental remediation with nanomaterials; nanomaterials in advanced energy storage; and obstacles and opportunities for the industrial use of nanomaterials.

Analytical Framework

The analysis was carried out using an integrated five-dimension framework. The first dimension, nanomaterial innovation, considers the impact of composition, morphology, surface chemistry, porosity, conductivity and functionality on the potential application. The second dimension, green synthesis, considers the minimization of harmful inputs and outputs, energy use and dependence on non-renewable resources in production routes. The third dimension, environmental remediation, covers the use of nanomaterials for water purification, wastewater treatment, pollutant adsorption, photocatalysis and environmental monitoring.

The fourth dimension, energy storage, investigates the applications of nanostructured materials in lithium-ion batteries, sodium-ion batteries, supercapacitors and new electrochemical devices. The fifth dimension, sustainability challenges, documents evidence of toxicity, exposure, lifecycle impacts, resource dependency, scalability, cost, regulations, recycling and industrial translation. These

dimensions are not independent: in assessing the functional benefit of a nanomaterial in a remediation or energy-storage application, it is important to consider how it was made, how it behaves in service and how it can be managed at the end of its life.

Trustworthiness and Credibility of the Research

Various types of documentary evidence (peer-reviewed research, review literature, institutional reports and standards-related publications) were triangulated to establish credibility. Using multiple source types reduced reliance on any single study and provided a more balanced interpretation of scientific claims. Dependability was achieved by describing the analytical process clearly and documenting the steps taken in developing the themes.

Confirmability was achieved by basing the interpretations on the content of the literature reviewed and by citing the literature according to the APA 7th edition format. The study distinguishes between information presented in the sources studied and the interpretive synthesis which the researcher has developed. Transparency was achieved by describing the research design, categories of evidence, criteria for evaluation, analysis procedure and limitations of the research. Consistency was maintained because the research questions, analytical framework, thematic findings, discussion, recommendations and conclusion all address the same research problem.

Ethical Considerations

This study does not involve human participants, animals or original laboratory experimentation, and therefore did not require conventional research-ethics approval. Ethical responsibility concerns the proper and respectful use of published knowledge. Ideas, findings, frameworks and interpretations taken from other sources are acknowledged through in-text citations and an APA 7th edition reference list.

The study does not plagiarize; it paraphrases, synthesizes and critically evaluates information and ideas from sources instead of copying text. It also seeks to avoid misrepresenting the strength of evidence by distinguishing what is established from what is emerging, what is methodological and what remains for future research. No fabricated authors, titles, journals, publication years, findings or institutional reports are included.

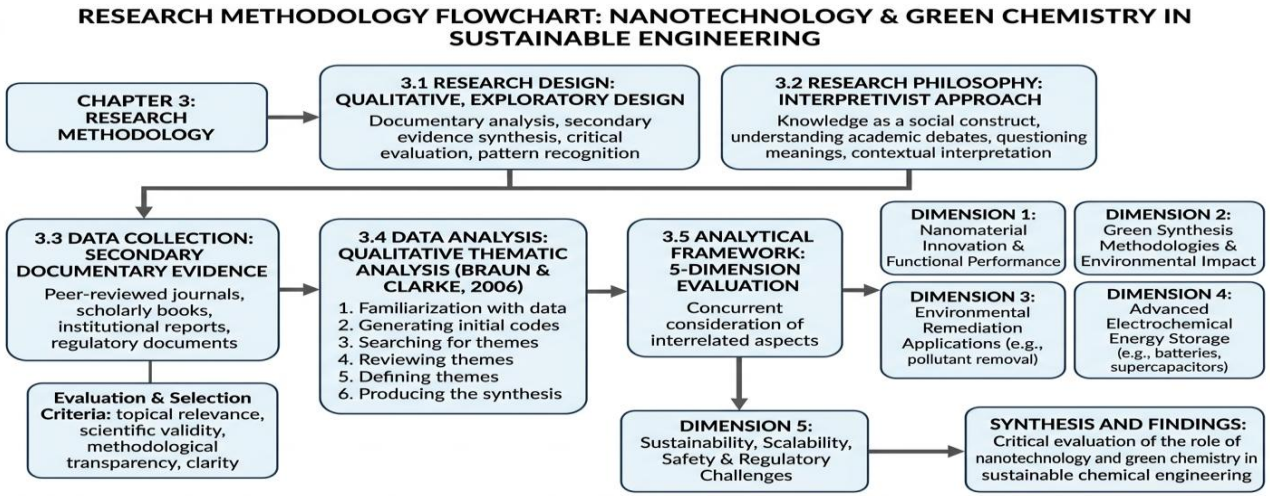
Methodological Limitations

The use of secondary evidence imposes several limitations. First, the study cannot verify the experimental results, materials characterization or reported performance of the materials presented in the literature surveyed. Second, the evidence could be subject to publication bias, that is, studies reporting positive remediation performance or improved energy-storage behaviour might be more likely to be published than studies reporting null or negative results.

Third, the materials, synthesis methods, experimental conditions, performance indicators and reporting practices differ across the works reviewed. This variation makes it hard to compare studies directly and makes it challenging to make generalizations across classes of nanomaterials. Fourth, sustainability assessments are often limited in scope, particularly in the case of long-term fate, toxicity, actual exposure, and end-of-life treatments. Finally, a documentary and interpretive study produces findings that are a critical synthesis of existing knowledge, not a specific evaluation of any particular nanomaterial, processes, or commercial technologies.

Figure 1 summarizes the research design, philosophy, data sources, analytical procedure and five-dimension analytical framework described above.

Figure 1: Research Methodology Flowchart



Findings

Five related findings emerged from the documentary evidence, organized by theme. Taken together, they show that nanomaterials have great potential in sustainable chemical engineering, provided that they are produced through green synthesis, designed according to responsible criteria, kept environmentally safe, evaluated across their life cycle and made viable for industrial use. The findings are based on critical interpretation of secondary evidence, not original experimental work.

Functional Innovation and Sustainability Potential

The first theme relates to the functional properties that make nanomaterials attractive for sustainable chemical engineering. Surface area, tunable porosity, surface functionalization, conductivity, catalytic activity, and structural stability are important properties mentioned repeatedly throughout the literature reviewed, and they relate to the various applications discussed: adsorption, catalysis, pollutant degradation, sensing, and electrochemical charge storage. Metal nanoparticles and metal oxide nanoparticles have been well documented as photocatalysts, adsorbents, antimicrobial agents and electroactive materials, while carbon-based nanomaterials are valued for their structural versatility, conductivity and adsorption capacity.

The evidence suggests that nanocomposites and hybrid structures may often overcome the limitations of traditional single-material structures. For example, semiconductors can be combined with carbon-based materials to improve charge separation in photocatalysis, and conductive carbon networks can be incorporated into battery electrodes to promote electron transport. Surface functionalization can also increase affinity for specific heavy-metal ions or organic pollutants. These innovation patterns suggest a shift towards multifunctional materials rather than materials designed for a single application.

However, the evidence also suggests that functional benefit does not necessarily translate into sustainability. A higher surface area increases the potential for pollutant removal or electrochemical activity, but it also increases reactivity, the tendency to aggregate and potential environmental interactions. Some porous materials require activation with solvents or metal-containing precursors, and some functionalization procedures introduce extra chemicals and make recycling difficult. The results therefore support a conditional interpretation: nanomaterials can contribute to more sustainable chemical engineering if their functional benefits outweigh the environmental burden of their synthesis, use, recovery and/or disposal.

Green Chemistry as a Foundation

The second theme concerns the contribution of green chemistry to the environmentally friendly and sustainable development of nanomaterials. Waste prevention, atom economy, the use of non-toxic solvents, renewable feedstocks, energy efficiency and minimization of toxicity recur throughout the literature as requirements for sustainable synthesis. Plant extracts, microbial systems, biopolymers and other biological agents are frequently presented as alternatives to the conventional reducing and stabilizing agents for the synthesis of metallic and metal oxide nanoparticles.

The literature suggests that green synthesis can be more attractive than conventional methods that use hazardous chemicals, because it often operates under milder conditions. Other reported pathways that may reduce solvent use or reaction energy include water-based, solvent-minimized, microwave, ultrasound and electrochemical processes. These follow the green chemistry objective of avoiding pollution at the design stage instead of trying to control it after production.

The results, however, indicate a tension in the research. Some studies suggest that biological methods and low-impact synthesis offer a more sustainable route, while others argue that repeatability, yield, particle-size control, scale-up and downstream purification still need to be resolved. The analysis shows that both perspectives are valid, but their relevance depends on the material, the application and the scale of production. A plant-based or biological route is not sustainable if it involves large amounts of solvent, hazardous residues or high energy use, or if materials cannot be recovered safely.

Perhaps the most important finding is the growing recognition of green chemistry as a system-level design principle rather than a property of a particular reagent or synthesis pathway. For sustainability to be truly realized, there needs to be evidence on sourcing of reagents, use of energy, generation of waste, toxicity, worker safety, scalability and end-of-life management. This interpretation supports safe-and-sustainable-by-design approaches, in which safety and sustainability are considered from early in the innovation value chain and throughout product development.

Nanomaterial-Based Environmental Remediation

The third theme relates to the use of nanomaterials in environmental remediation. The documentary evidence covers research on the use of nanomaterials for water purification, wastewater treatment, heavy metal removal, photocatalytic degradation, membrane-based separation, detection and antimicrobial treatment. These materials possess high surface area and modifiable surface chemistry, which allow them to bind pollutants, including heavy metals, dyes, pharmaceuticals, pesticides and pathogens.

Adsorption is the most commonly reported remediation pathway. For binding toxic ions and organic compounds, carbon-based materials such as graphene-based materials, carbon nanotubes, biomass-derived carbons, metal-organic frameworks and functionalized nanoparticles can be utilized. Surface modification can improve selectivity, and magnetic or easily separable structures can improve recovery after treatment. Based on these results, it is suggested that the use of nanomaterials could lead to enhanced selectivity and flexibility of water treatment systems.

Photocatalysis, particularly for organic pollutants, is the complementary pathway. Under illumination, semiconductor nanomaterials such as titanium dioxide, zinc oxide and nickel oxide generate reactive species that degrade dyes, pharmaceutical residues and other organic pollutants. Composite photocatalysts are frequently proposed to increase visible-light response, charge separation and stability. The literature also highlights that degradation does not automatically mean detoxification, because unknown or even harmful transformation products may be formed.

The results also indicate persistent practical limitations. Real wastewater differs from laboratory solutions in pH, competing ions, natural organic matter and complex pollutant mixtures, all of which can affect adsorption effectiveness. The availability of light, recovery of the photocatalyst, the design of the reactor, and catalyst deactivation can limit photocatalytic systems. The aggregation, dissolution or release of nanoparticles into treated water may create secondary pollution. Regeneration, reuse and final disposal therefore matter not only technically but also for sustainability.

A common gap in remediation studies lies between laboratory performance and operational feasibility. Several studies have demonstrated removal under controlled conditions, but very few have examined long-term stability, real effluent matrices, regeneration cycles and environmental release. It is therefore recommended that studies be carried out within integrated treatment systems that consider pre-treatment, material recovery, regeneration, monitoring and safe disposal.

Nanomaterials for Advanced Energy Storage

Nanomaterials' role in sustainable energy storage is the fourth theme. The literature shows that ion transport, electronic conductivity, charge transfer kinetics, stability of the electrodes and interfacial behaviour can be modified by nanostructuring. These properties are relevant to lithium-ion batteries, sodium-ion batteries, supercapacitors and emerging electrochemical storage systems. Nanotechnology is also used in electrodes, conductive additives, separators, electrode interfaces and hybrid electrode architectures.

The literature discusses the use of carbon-based nanomaterials, metal oxides, silicon-based structures and nanocomposites to enhance conductivity, minimize volume changes and maximize electroactive surface area in lithium-ion batteries. For sodium-ion batteries, nanomaterial engineering is explored to enhance sodium-ion diffusion, electrode stability and cycling. The literature suggests that, despite their potential advantages, sodium-ion systems still face several challenges, such as energy density, electrode durability and commercial scalability.

The key components of supercapacitors are high-surface-area carbon materials, conductive networks and pseudocapacitive materials. Nanomaterial engineering can help achieve fast charge/discharge characteristics and long cycle life, particularly where short-term power buffering is needed. To balance energy density and power density, hybrid supercapacitors combine battery-type and capacitor-

type charge storage. These results show that nanomaterials can expand the electrochemical storage design space beyond existing battery chemistries.

Yet improved electrochemical performance is not enough to prove sustainability. The materials in batteries and supercapacitors can include lithium, cobalt, nickel, graphite and other materials that are hard to obtain and difficult to process and recycle, causing environmental and supply-chain problems. Sodium-ion options appear to provide an alternative to some critical materials, but only with responsible sourcing, long-life electrode design, efficient production and end-of-life recovery. The literature is therefore converging on a shift from performance assessment to life-cycle assessment of energy-storage technologies.

Economic and Environmental Drivers and Constraints of Sustainability

The final theme relates to barriers and opportunities for industrial implementation. The toxicity, persistence in the environment, uncertainties of exposure, impacts of the lifecycle, production cost, scalability, resource dependence, and regulatory complexity are all recurring themes that were mentioned in the evidence reviewed. These concerns stem partly from characteristics that make nanomaterials behave differently from bulk materials, and partly from the difficulty of characterizing their hazards and exposures because of their small size, surface reactivity and potential mobility.

OECD publications also note that rapid innovation in nanotechnology might outpace the development of suitable risk assessment techniques and regulation. Safe-and-sustainable-by-design strategies aim to minimize this gap by integrating hazard, exposure and sustainability into the product lifecycle as well as the innovation process. ISO guidance on handling manufactured nanomaterials also emphasizes documentation, risk management, information disclosure, and occupational health and safety.

Life-cycle assessment (LCA) is becoming an important tool for more responsible decision-making. Life-cycle thinking can reveal burdens that are not apparent in research on pollutant removal or electrochemical performance. However, the literature reviewed reports several limitations of LCA for nanomaterials: the lack of inventory information, uncertainty about environmental fate, and limited information about industrial scale production.

The results show that circular-economy measures (e.g., adsorbent regeneration, material recovery, battery recycling and design for disassembly) are potential sustainability measures, but not necessarily solutions in themselves. Recovery may require energy input or separation processes, and nanocomposites and contaminated adsorbents are difficult to recycle. The opportunity lies in designing materials and products with recovery in mind, rather than attempting recovery only at the end.

Finally, the results suggest that sustainable chemical engineering is not just about asking “Does it work?” but also “Does it work safely, efficiently, fairly and reversibly within the wider industrial system?” The potential of nanomaterials to advance sustainability is best realized when LCA, safe-and-sustainable-by-design approaches, regulatory preparedness and circular materials management work hand in hand.

Discussion

Nanomaterials in Sustainable Chemical Engineering

New nanomaterial design principles are expanding the scope of chemical engineering. Metal and metal-oxide nanoparticles can be used for various photocatalytic, redox or adsorption reactions as well as for antimicrobial activity, conductive platforms can be developed from carbon-based nanomaterials, and nanocomposites can be designed to counteract the limitations of their components. In environmental applications, this expands the range of treatable pollutants, such as heavy metals, dyes, pharmaceutical residues and other emerging pollutants. In energy technologies, nanostructured electrodes shorten transport distances, improve interfacial contact and accommodate structural changes during cycling.

However, there is no simple link between functional performance and sustainability. A material with high adsorption capacity may be difficult to regenerate, and a highly active photocatalyst might need ultraviolet light, become deactivated or produce incompletely characterized transformation products. Similarly, a nanostructured battery electrode might show enhanced charge-transfer behaviour but depend on rare metals or expensive synthesis. According to the literature reviewed, improved functional performance is therefore a necessary but not sufficient condition for sustainability.

This interpretation goes against the grain of a common practice in nanotechnology research of equating efficiency with sustainability. While the efficiency of pollutant removal or energy storage is important, it needs to be considered through the lens of resource use, emissions, toxicity, durability, recoverability and end-of-life impact. Sustainable chemical engineering requires an expanded decision

space: does the nanomaterial work well, and is it better than the available alternatives when its production, use and recovery are considered?

Green Chemistry and Responsible Development

Green chemistry offers the most immediate approach to bringing innovation in nanomaterials in harmony with sustainability. Waste prevention, atom economy, safer solvents, renewable feedstocks, energy efficiency and reduced toxicity are all areas of focus for reducing the environmental impacts of the manufacture of nanomaterials. Plant-based, microbial and other biological synthesis routes are attractive because they are likely to require milder reaction conditions and to use renewable feedstocks, while water-based, solvent-minimized, microwave-assisted, ultrasound-assisted and electrochemical synthesis methods are likely to be less energy intensive or less solvent intensive.

The findings, however, indicate that green synthesis should not be regarded as a simple substitute for conventional synthesis. If a biological reducing agent involves substantial solvent extraction, produces harmful residues, gives low yields, or cannot be reproduced and scaled up, the process cannot be regarded as sustainable. Similarly, substituting a single hazardous reagent may not improve overall sustainability if the new reagent requires more energy, water or purification. What distinguishes genuinely environmentally friendly synthesis from a modestly modified conventional synthesis is the scope of the assessment.

Responsibility can therefore be built in during the development phase of a material, through less hazardous precursors, reduced solvent and energy use, improved atom economy, recovery, and design for safe handling after use. The OECD's safe and sustainable by design approach is aligned with this view, as it encourages the integration of safety and sustainability from the beginning and all the way through the innovation value chain.

Environmental Remediation and Ecological Implications

The use of nanomaterials in remediation is a promising approach for treating water and removing pollutants that traditional methods cannot easily remove. Persistent contaminants such as heavy metals, organic dyes and pharmaceutical residues can be addressed through adsorption, photocatalysis, membrane modification and nanosensing. These applications are particularly pertinent in the face of growing challenges in water systems with conventional and emerging contaminants.

The ecological effects, however, remain unclear. Nanoparticles may aggregate, dissolve, leach or remain suspended during water treatment. If separation or regeneration processes are inefficient, remediation can turn a water-pollution problem into a solid-waste or nanoparticle-release problem. Transformation products are another concern in photocatalytic degradation, because the degradation of a parent pollutant does not imply complete detoxification.

Regeneration and reuse are particularly important for adsorption systems. If reusing the adsorbent is not economically feasible, substantial amounts of contaminated adsorbent waste will be generated. Conversely, maintaining stable performance over repeated cycles could be a more sustainable solution, as long as regeneration can be achieved without using too much energy and dangerous chemicals. The literature therefore shows a shift away from short-term performance testing towards longer-term assessment in real matrices, including recovery.

Energy Storage and Sustainable Transitions

Nanomaterials also have a significant contribution to make to the transition towards a more flexible, low-carbon energy supply. Nanostructured electrodes, conductive carbon networks and engineered interfaces can improve lithium-ion batteries, sodium-ion batteries and supercapacitors by enhancing ion transport, electronic conductivity, charge-transfer kinetics, cycling stability and other properties. These enhancements can support the integration of renewables, because energy-storage systems must respond quickly to fluctuations in electricity demand and supply.

However, the viability of energy storage depends on more than electrochemical properties. The mining, processing and recycling of materials in lithium-ion technologies pose environmental and supply-chain problems. Although sodium-ion batteries hold promise as a technology less reliant on certain critical materials, they still need greater economic scalability, more durable electrodes, safe electrolytes and effective end-of-life management. This study therefore implies a more nuanced picture: sodium-ion technologies may offer resource advantages, but only if they are examined in their entirety.

Electrode degradation and recyclability require particular attention. Nanoscale materials may increase surface activity and side reactions, and their separation and recovery may be difficult because of complex electrode structures. Sustainable energy-storage

devices should therefore be developed using materials that are easily recyclable, low in toxicity, efficiently manufactured, designed for disassembly and valuable once recycled.

Integrating Environmental and Energy Applications

The most significant aspect of the study is its integrated interpretation of environmental and energy applications. Environmental remediation and energy storage are usually studied independently, but share the same key material design principles, such as surface area, porosity, conductivity, catalytic activity, stability, and functionalization. They also face the same sustainability challenges relating to synthesis impacts, material safety, scale, resource use and end-of-life.

These dimensions can be connected in an integrated sustainable chemical-engineering framework. Such a framework would evaluate a nanomaterial not only for its ability to remove a pollutant or store charge, but also for the environmental impact of its manufacture, its safety in use, its recyclability and the value of the materials recovered. This can help prevent problem shifting, where a benefit in one part of the system becomes a harm in another.

Integration can also create synergies. For example, biomass-derived carbon materials are used both as low-impact adsorbents in water treatment and as conductive materials in energy-storage electrodes. Similarly, recovery strategies developed for batteries could inform the recovery of nanomaterials from treatment systems. These options remain largely unexplored and represent an important pathway for interdisciplinary research.

Comparison with Previous Studies

The findings corroborate recent peer-reviewed research indicating that nanomaterials are promising but not yet proven enablers of environmental and energy sustainability. Water-treatment studies cite high surface area, tunable chemistry and multifunctionality as benefits, while scalability, recovery, toxicity and real-world performance are seen as drawbacks.

The results are also consistent with the energy-storage literature, which argues that nanostructuring can enhance electrochemical properties but will not resolve resource, recycling or manufacturing issues. Reviews of lithium-ion and sodium-ion technologies similarly emphasize the need to consider not only performance but also resource availability, durability, safety and life-cycle effects.

At the same time, the present analysis identifies a gap in the literature, as many studies focus on one aspect of sustainability while neglecting others. Remediation studies may focus on pollutant-removal ability without assessing the burden of synthesis or nanomaterial release. Energy-storage studies may focus on capacity and cycling stability while paying less attention to resource origins or material recycling. Green-synthesis studies may emphasize benign inputs without demonstrating life-cycle benefits. This fragmentation shows the importance of interdisciplinary, integrated and transparent sustainability research.

Theoretical and Practical Implications

Theoretically, the study contributes to sustainable chemical engineering by proposing that nanomaterial innovation be considered in light of integrated features: functionality, green synthesis, eco-safety, resource efficiency and circularity. This perspective looks beyond performance and treats sustainability as a property of the whole technological system.

In practice, the results imply a need for partnership between disciplines, namely chemical engineers, materials scientists, environmental scientists and policymakers. For industrial implementation, laboratory proof of concept must be followed by production that is scaled up safely and economically, in compliance with regulations and with viable recovery pathways. These results thus give credence to responsible innovation, and not to the uncritical uptake of technology.

Critical Synthesis

Sustainability needs to be measured in more than technical terms, because technical performance alone does not show where, or by whom, environmental costs are borne. A nanomaterial may be highly effective at eliminating pollutants yet be manufactured with hazardous chemicals, or it may make a better battery yet be made from scarce materials that are complex to recycle. Lifecycle thinking and principles of circular economy, material safety and responsible innovation should, therefore, be integrated into the sustainability assessment process.

The study also shows that nanomaterials and green chemistry can be part of sustainable chemical engineering if the innovation process is conducted in accordance with the principles of precaution, transparency and systems-level assessment. Whether materials can be made to work in the laboratory matters much less than whether they can be produced, applied, recovered and governed responsibly at scale.

Recommendations

Sustainable Nanomaterial Synthesis

Synthesis pathways, research and industrial development should seek to reduce hazardous inputs, waste, energy use and reliance on non-renewable resources. Green chemistry principles should be applied as a whole, not selectively, including atom economy, safer solvents, renewable or waste-derived feedstocks and process intensification. Water-based and solvent-minimized systems are recommended where chemically appropriate, and microwave, ultrasound, electrochemical and mechanochemical methods should be evaluated in terms of energy use and waste.

Biological synthesis should be encouraged where it is shown to be reproducible and scalable and to offer a demonstrable environmental advantage. Solvent use, energy requirements, precursor hazards, purification needs, waste streams and material recovery potential should be reported. This would make it easier to differentiate genuinely sustainable synthesis from synthesis that is labelled “green” simply because it uses plant extracts or biological reagents.

Assessing Environmental Safety and Risks

Safety assessment of nanomaterials should begin at the earliest stage of research, not after development. Toxicological studies should address toxicity, environmental mobility, persistence, aggregation, dissolution, leaching, exposure pathways and potential secondary pollution. Special care should be taken with nanomaterials used in open or semi-open environmental systems (e.g., water treatment, soil remediation and agriculture).

Industrial and research institutions should adopt safe handling procedures in line with accepted nanotechnology safety guidelines. Laboratory and manufacturing procedures should clearly set out occupational exposure controls, containment measures, personal protection, and waste segregation and documentation. Standards-related guidance from ISO and the OECD can support consistent risk-management approaches.

Environmental Remediation Applications

Real-world operating conditions should be considered when developing nanotechnology-based water and wastewater technologies. Further studies should evaluate performance in matrices with varying competing ions, natural organic matter, pH and mixed pollutants. Adsorption studies should account for regeneration, reuse, material recovery and final disposal, and photocatalytic studies should identify transformation products and determine whether degradation amounts to true detoxification.

For industrial use, nanomaterial-based systems should be easy to integrate into current treatment systems, easily recovered, and should have minimal secondary waste. Membrane modification, immobilized catalysts, magnetic separation, and regenerable adsorbents could be practical avenues for minimizing the release of nanoparticles, but durability, cost, and environmental safety must be assessed for each of these methods.

Sustainable Energy Storage

Energy-storage research needs to go beyond capacity and cycling performance to consider resource efficiency, durability, safety, recyclability, and environmental impact. Nanostructured electrode design should aim to minimize dependence on critical materials, increase service life and enable the recovery of valuable materials. Sodium-ion batteries, supercapacitors and hybrid systems should be evaluated as complementary technologies rather than as replacements for lithium-ion systems.

Manufacturers should focus on electrode architectures that allow easy disassembly and material recovery. Less harmful electrolytes, stable interfaces, minimized cobalt or nickel content (where possible), and recycling options that are suitable for nanoscale electrode structure must also be explored. These measures can link the development of energy storage to the goals of the circular economy.

Lifecycle Assessment and Circular Economy

For both remediation and energy storage, the development of nanomaterials should include lifecycle assessment as an integral part. The assessments should include raw-material sourcing, synthesis, manufacturing, transport, use, regeneration, recycling, and disposal. To allow meaningful comparison between technologies, system boundaries, assumptions, data quality and uncertainty must be communicated transparently.

Circular economy strategies must be integrated from the beginning of the design of materials and products. Adsorbents should be regenerable, photocatalysts recoverable and battery materials suitable for recycling. However, circularity must be substantiated rather than taken for granted, because recovery processes can consume energy or produce waste.

Industrial Implementation

Immediate industrial action should focus on applications that are scalable, safe and economically viable. Laboratory innovation must be connected with manufacturing needs, regulatory expectations, and markets, through collaboration among chemical engineers, materials scientists, environmental specialists, industrial organizations and policymakers. Before widespread deployment, pilot-scale demonstration, quality control, process safety and supply-chain transparency should be established.

Policy & Regulatory Development

Policy development should promote responsible governance of nanotechnology by providing clear safety guidelines, environmental monitoring protocols, risk-communication programs, and standards for the characterization of nanomaterials. Regulatory systems should be able to address particle size, surface chemistry, agglomeration state and life-cycle stage, not only chemical composition.

Future Research Priorities

Longer-term research should address the functionality of nanomaterials together with their safety, feasibility and life-cycle sustainability. Standardized sustainability measurements, field performance of remediation materials, nanomaterial fate and transport, safe scale-up, recyclable energy-storage materials, and systems integration are among the priority areas. Throughout nanomaterial innovation, interdisciplinary research will play a crucial role in ensuring that nanomaterials genuinely advance the sustainability agenda rather than undermine it.

Conclusion

The main aim of this research work was to explore, using a qualitative, interpretivist, exploratory and documentary approach, the role of advances in nanomaterials and green chemistry in sustainable chemical engineering, specifically for the purposes of environmental remediation and energy storage. Its importance lies in addressing a fragmented research field in which nanomaterial performance, green synthesis, environmental safety and industrial feasibility are treated separately. The study concludes that nanomaterial innovation can contribute to sustainability but should be assessed from a broader perspective that considers not only technological function but also environmental safety, resource efficiency, life cycle impacts, and responsible governance.

The analysis demonstrates that advanced nanomaterials have functional properties that are useful in several sustainable chemical-engineering applications. The high surface area, tunable chemistry, catalytic activity, conductivity, adsorption capacity, and structural versatility make metal and metal-oxide nanoparticles, carbon-based materials, graphene-related structures, carbon nanotubes, nanocomposites and porous functionalized materials attractive. They can be used for applications such as pollutant adsorption, photocatalytic degradation, membrane treatment, environmental sensing and electrochemical energy storage. The study also shows that these functional benefits come with strings attached: higher performance at the nanoscale can be accompanied by increased reactivity, recovery difficulties, resource use, or environmental effects.

Green chemistry is a basic paradigm for the responsible development of nanomaterials. Synthesis routes can be designed to reduce environmental impacts using principles including waste prevention, atom economy, safer solvents, renewable feedstocks, energy efficiency and reduced toxicity. Biological, water-based, solvent-minimized and energy-efficient synthesis routes are now being explored as alternatives to conventional methods; they show potential but need to be evaluated holistically. The use of a plant extract or biological reagent cannot be considered evidence of a sustainable process until total solvent consumption, energy requirements, waste production, repeatability, scale-up and end-of-life are taken into account.

In environmental remediation, nanomaterials are crucial to pathways for water purification, wastewater treatment, heavy metal removal, photocatalytic degradation, and management of emerging pollutants. Their large surface area and functional surfaces can enhance the removal of toxic ions and organic contaminants, and semiconductor nanomaterials can help in the degradation of dyes, pharmaceutical residues and other persistent substances. However, the study concludes that remediation potential needs to be weighed against the potential for release of nanoparticles, toxicity, aggregation, regeneration and secondary contamination. Effective pollutant removal must be coupled with systems that can be recovered, regenerated, and reused safely over time for sustainable remediation.

The study also underscores the importance of nanomaterials in developing future energy-storage systems. Ion transport, charge-transfer behaviour, electrode stability and cycling performance in lithium-ion batteries, sodium-ion batteries and supercapacitors can be affected by nanostructured electrodes, conductive carbon networks, engineered interfaces and hybrid materials. These are significant for the integration of renewables and electrified technologies. However, the analysis reveals that electrochemical attributes do not necessarily indicate sustainability in energy storage. Resource availability, mining impacts, manufacturing energy use, electrode degradation, reusability and end-of-life management remain key issues.

The main challenges identified in environmental and energy applications are closely related. Issues that can limit industrial implementation include uncertainty about exposure pathways, nanotoxicity, environmental persistence, critical-resource dependence, limited recyclability, high production cost, and limited regulatory preparedness. These challenges point to the need for more than laboratory-scale proof of concept for sustainable innovation. Such innovation demands scalable manufacturing, safe handling, clear risk assessment, material recovery and policy strategies that can address the unique characteristics of engineered nanomaterials.

The study makes a theoretical contribution by integrating nanomaterial innovation and green chemistry within sustainable chemical engineering. The study shows that the fields of remediation and energy storage require similar material-design principles and sustainability limitations, and that they are not separate technological fields. From a practical standpoint, the results support a paradigm shift from performance-based development to safe-and-sustainable-by-design development, in which environmental safety, resource efficiency, circularity and industrial feasibility are taken into account from the outset of research and development.

Interdisciplinary efforts involving the integration of material functionality, lifecycle assessment, environmental fate, toxicity testing, scalable green synthesis, recyclable electrode design and real-world remediation performance should be encouraged. More should also be done to develop standardized sustainability metrics, increase transparency in reporting, and create circular pathways for recycling nanomaterials from water-treatment and energy-storage systems.

In conclusion, the potential long-term impact of nanomaterials for sustainable chemical engineering will depend not only on their technological capability but also on their environmental safety, life-cycle sustainability, responsible production and resource efficiency. Nanomaterials, in combination with green chemistry, can contribute to cleaner industrial processes, effective environmental protection and more resilient energy systems, but this will require innovation that is scientifically robust, industrially viable, ethically sound, and precautionary.

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