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REVIEW

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Towards net-zero nanotechnology: Green materials, sustainable manufacturing, and circular nanoeconomy-A comprehensive review

Tanzeer Ahmad Dar[1], Sujatha Gundeboiyna[1], T. Vedavathi[1], G. Prathibha[2] and Nazir Ahmad Mala[3]

[1]Department of Chemistry, Audisankara (Deemed to be University), Gudur-524101, Andhra Pradesh

[2]Department of Physics, CMR College of Engineering & Technology, Kandlakoya, Medchal-501401, Hyderabad

[3]Department of Agro-Industry, Chiang Mai University, Chiang Mai-50100, Thailand

ABSTRACT

Nanotechnology is at a turning point. Beyond its revolutionary technical potential, the field is also becoming the subject of increased concern with regard to the materials and energy that are used to create nanomaterials, as well as the materials and energy used in their use and disposal. With the race to Net Zero growing in pace, there is a parallel challenge for the nanotechnology community to maximise engineering outcomes with minimal environmental harm at the nanoscale. The review summarizes the existing knowledge on the upcoming strategy of the 'net-zero nanotechnology' along with three interconnected dimensions: (1) green materials and synthesis including (phyto- or microbial) biosynthesis, green solvents and bio-based nanomaterials; (2) sustainable nanomanufacturing, including the principles of green nanotechnology, atom effective process design and utilizing Artificial Intelligence (AI)/ Machine Learning (ML) for nanomanufacturing; (3) nanotechnology circular economy, end-of-life recovery of nanomaterials (carbon, composites), recovering resources from e-waste and mining streams, and the EU's policies (Net-Zero Industry Act (NZIA) and Critical Raw Materials Act (CRMA)). Environmental hotspots are mapped throughout the nanomaterial's lifecycle, and principles are outlined for taking nanomaterials into applications that are already demonstrating quantifiable performance gains in renewable energy, carbon capture, water treatment and sustainable farming. This review provides a single lens on common challenges encountered in the development of nanotechnology that have otherwise existed in separate worlds, such as green synthesis, sustainable production and circularity, with a research agenda to connect the dots of nanotechnology with global net-zero/ circularity goals.

KEYWORDS

Net-zero nanotechnology; Green synthesis; Sustainable nanomanufacturing; Life cycle assessment; Circular nanoeconomy; Nanotoxicology

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Introduction

Nanotechnology is the understanding and control of matter predominantly at the nanoscale (approximately 1–100 nm), where size- and structure-dependent properties and phenomena emerge that differ from those of individual atoms or molecules or of larger-scale materials, and which enables the imaging, measuring, modelling, and engineering of matter at this length scale into new structures, devices, and systems (per ISO/TS 80004-1 and the U.S. National Nanotechnology Initiative usage). The extraordinary optical, electronic, catalytic and mechanical properties, depending on the size of nanomaterials, have been used to make step-changes in device functionality that cannot be matched by bulk materials. But until recently, this same technology development momentum has advanced largely uncoordinated with the parallel ongoing global drive for industry decarbonization and for achieving Net Zero GHG emissions by 2050 [1].

Chemical reduction, sol-gel processing, chemical vapor deposition, hydrothermal and solvothermal methods are the conventional routes that have been employed to synthesize nanomaterials, but they often involve the use of hazardous reducing/capping agents, high-temperature heating or vacuum evaporation, or organic solvents with high embodied carbon. The GWP and energy demand category measured for cumulative energy use in raw-material and precursor production and the embodied energy of the solvents and reagents typically make up 60-80% of the life-cycle impact of nanomaterial production in a life-cycle assessment analysis [2-4].

Meanwhile, another stream of research has also developed on three interlocking themes which are considered the three pillars of the 'net-zero nanotechnology' agenda, and as this review shows, there are countervailing arguments on these themes. First, Green materials, replacing dangerous reactants present in conventional chemistry with plant extracts, microbial and fungal metabolites, algal biomass, as well as green solvents like Deep Eutectic Solvents (DES) and ionic liquids, and creating a preference for renewable and bio-based feedstocks like cellulose. Particularly, their 2D invention is sustainable nanomanufacturing the creation of nanomaterials using design principles and approaches in green chemistry, typically using high-speed and energy-efficient process intensification and becoming more and more common AI and ML to optimize the reaction process conditions, lower amount of solvents and energy used for their manufacturing, and to speed up the process to create new safer formulations. The third is the circular nano economy: end-of-life strategies for nanomaterials recovery and recycling; recovery of metals and carbon nanomaterials from electronic waste and mining tailings; and policy for resilient, lower-carbon supply chains for the raw materials critical for much of today's advanced nanomaterials [1,5-8].

This review aims to collect the current literature on these three pillars with a focus on the more recent literature (2023-2026). As well as outlining systems and methods of synthesis and application, we encompass the burgeoning evidence base for life-cycle assessment and nanotoxicology that is needed to help properly evaluate whether a particular green or sustainable method actually is reducing overall environmental footprint, rather than simply moving it somewhere else. Finally, we identify the major obstacles (standardization,

***Correspondence:** Dr. Tanzeer Ahmad Dar, Department of Chemistry, Audisankara (Deemed to be University), Gudur-524101, Andhra Pradesh. email: tanzeerchem21@gmail.com

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scalability, cost, regulatory harmonization and data availability) to moving laboratory-scale green nanotechnology towards an industrially based, net-zero oriented circular nano-economy (Figure 1).

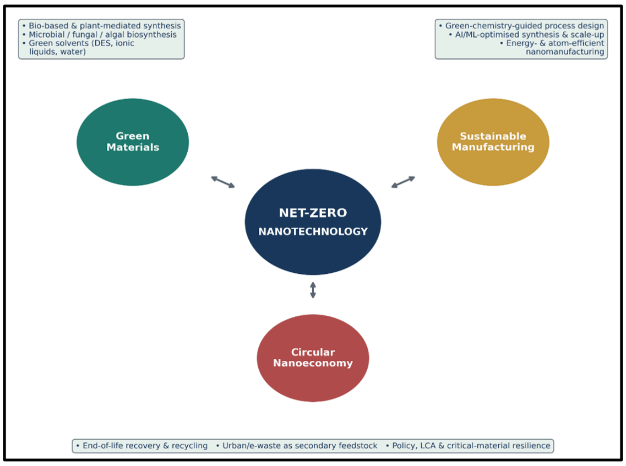

Figure 1. Conceptual framework linking green materials, sustainable manufacturing, and the circular nano economy within a net-zero nanotechnology agenda.

Green Materials for Nanotechnology

Throughout this review, "green" is used to denote a chemistry or process attribute (e.g., non-toxic reagents, renewable feedstocks, reduced hazard), whereas "sustainable" is used in the broader life-cycle and systems sense (net environmental, economic, and social performance over the full value chain); a synthesis route can therefore be green at the point of reaction while remaining non-sustainable overall if, for example, upstream extraction or downstream energy demand is high - a distinction developed further via the life-cycle assessment evidence in Section 6. Substituting toxic chemical reagents with biological or benign chemical reagents is the most widely studied aspect of sustainable nanotechnology. At a general level, the green synthesis processes are classified into four overlapping groups: photosynthesis, microbial and fungal biosynthesis, algal (phyconanotechnology) synthesis and green solvents as reaction media. They are further discussed below, and the discussion also includes bio-based structural nanomaterials, like nanocellulose [5,7-9].

Plant-mediated (Phyto-) synthesis

In the plant-mediated synthesis, the metal ions are reduced and capped using natural substances, viz polyphenols, flavonoids, terpenoids and reducing sugars present in the phytochemical profile of the plant extracts used for the process, instead of strong reducing agents (sodium borohydride, hydrazine) and capping agents used in the conventional wet-chemical synthesis. Plant species, e.g. *Ocimum sanctum* (tulsi), *Curcuma longa* (turmeric), *Azadirachta indica* (neem) and *Moringa oleifera* have been studied for the synthesis of silver, gold, zinc oxide, copper oxide, iron oxide and bimetallic oxide nanoparticles with controlled morphology and crystallinity [10-17].

All the recent comprehensive review papers up to the 2021-2025 literature indicate that the plant-mediated pathways are more likely to obtain an enhanced colloidal stability, low synthesis costs and less harsh reaction conditions than the microbial and enzymatic pathways; as well as identifying persistently inconsistent results in the standardization process both within and between different plant species and extraction protocols and within different reaction conditions which prevents achieving batch-to-batch consistency. Fabrication of photosynthesized bimetallic and binary metal-oxide systems such as $ZnCo_2O_4$, $ZnFe_2O_4$ and $ZnO–ZrO_2$ composite oxides illustrates the expanded versatility of phyto-synthesis technology to more complex combinations of materials for catalysis and environmental applications. Some of the potential applications of plant-based nanoparticles include antimicrobial therapeutics, drug delivery, tissue engineering, and degradation of dyes through photocatalytic reaction and the removal of heavy metals from industrial effluents [10-15,18-22].

The balance between accessibility and reproducibility has been observed throughout the synthesis of plant-based nanoparticles, as phytochemical contents depend on plant species, geographical location, season, and extraction process, which means that batch-to-batch current size, shape and yield of nanoparticles from plant extracts is difficult to predict and regulate for scale-up in industry [5,21].

Microbial, fungal, and algal biosynthesis

In addition, there is an alternative biological pathway relating to the synthesis of nanoparticles through three mechanisms: enzymatic reduction (typically a family of enzymes called NADH/NADPH-dependent reductases), redox metabolism, and interactions with functional groups at the cell surface or in the cytoplasm of microorganisms (bacteria, fungi, yeast, cyanobacteria, and microalgae). One particular advantage of fungal-mediated synthesis is its ability to produce multimetallic nanoparticles in which secreted extracellular enzymes and metabolites act as reducing, capping and stabilizing agents simultaneously; some of the fungi, such as *Trichoderma reesei* and *Neurospora crassa*, can produce bimetallic nanoparticles with a strong antimicrobial effect (bimetallic and trimetallic systems (Ag–Au, Cd–Hg), etc) [23,24].

The bacterial and yeast-mediated synthesis share similar enzymatic pathways and have been utilized widely in the field of nanotechnology applications in agricultural biotechnology for microbial synthesis of nanoparticles for pest control, nutrient supply and soil restoration. Algal and cyanobacterial synthesis, known as phyconanotechnology, has become a scalable approach that involves the making of spherical nanoparticles (10–100 nm) that are effective against more than 70 bacterial species, making algal biosynthesis a promising way to address antimicrobial resistance [25-28].

The advantages over microbial routes are ambient reaction conditions, no need to use hazardous reagents, and adherence to continuous operation processing in bioreactors; the disadvantages, for both microbial routes, are slower reaction rates compared to chemical synthesis, intracellular synthesis leading to polydispersity, and the complexity of microbial cultivation and maintenance at a production scale [24,25].

Green solvents: Deep Eutectic Solvents (DES) and ionic liquids

Solvents are among the most significant sources of the many aspects of embodied energy and embodied toxicity associated with conventional manufacturing of nanomaterials. Since first reported by Abbott et al. rather than selecting a common organic solvent, DES are among the most popular options for alternative green solvents in the synthesis of nanomaterials. Abbott et al. first reported the formation of DES composed of two components, choline chloride and urea, in defined molar ratio resulting in an eutectic mixture with a very low melting point, which is room temperature stable. This finding identified DES as a subfamily of designer solvents with low toxicity and biodegradability, and tunable physicochemical properties that have, in turn, been employed for the green synthesis of nanomaterials [29-32].

The mechanism in which DES play a role in the synthesis of nanomaterials involves them in several ways: as reaction media, simply providing the liquid environment where reactions are encouraged to occur; as active participants, functioning as reducing or capping agents, in addition to their role as a reaction medium. Some of the reported applications include wet-chemical nanoparticle precipitation, fabrication of reticular (framework) materials, electrodeposition/ electrochemical synthesis of nanostructures, and morphology control, such as one-step production of hematite nano-spindles from choline-chloride/urea DES for controlled precipitation

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of ZnO nanostructures. Unlike conventional hydrothermal or solvothermal processes, which tend to be high-temperature/high-pressure, DES operate at lower temperatures and pressures, so they consume less energy and do not risk environmental contamination that conventional, high-temperature and high-pressure processes can [30,32-35].

There is growing interest in machine-learning-guided design of DES, and a few interesting examples exist where predictive models can speed the search for DES in emerging applications like cathode recycling for lithium-ion batteries and rare-earth elements extraction, which weaves into the themes of green solvents and AI in manufacturing discussed in Section 3.3. Natural deep eutectic solvents (NaDES) and other Ionic Liquids derived from naturally occurring organic compounds are currently being investigated for pharmaceutical applications, pushing the green solvents toolbox towards additional nanomaterial applications in the pharmaceutical and materials sector [36,37].

Bio-based structural nanomaterials: Nanocellulose and beyond

The other critical strand of green materials that goes beyond nanoparticle synthesis is the structural and functional nanomaterials directly sourced from renewable biomass. The most widely studied type is nanocellulose, which includes cellulose nanocrystals (CNC), cellulose nanofibrils (CNF) and bacterial nanocellulose (BNC). Nanocellulose is a high-strength, biodegradable, innocuous substance isolated from wood pulp, agricultural residues, and bio-waste from agriculture, and more recently, other types of lignocellulosic biomass; it exhibits characteristics very similar to the extracellular matrix and shows good potential to be used in drug delivery, wound healing, and tissue engineering applications. [38-41].

The combination of the mechanical stability and the functional group density of the nanocellulosics overcomes the limitations of the mechanical instability and non-functional MOFs. Market analyses indicate the global nanocellulose market is projected to reach more than US $2.1bn by 2032, at a compound annual growth rate of nearly 23.5%, and the interest in sustainable, bio-based nanomaterials is on the rise [39, 42-45].

A variety of renewable feedstocks are being explored, including lignin nanoparticles obtained by functional DES, chitin/chitosan nanostructures and carbon nanomaterials derived from agricultural wastes that form an alternative supply chain for nanomaterials based on renewable resources while providing a transition toward a bio-based supply chain that is compatible with the circular economy (Table 1) [46-48].

Table 1. Comparative overview of green synthesis routes for nanomaterials.

Synthesis route	Typical precursors / mediating agents	Proposed mechanism	Key advantages	Key limitations
Plant-mediated (phyto-synthesis)	Leaf, root, fruit or seed extracts (e.g., neem, tulsi, turmeric, Moringa oleifera)	Phytochemicals (polyphenols, flavonoids, reducing sugars) reduce and cap metal ions.	Low cost, ambient conditions, wide plant availability, good colloidal stability	Batch-to-batch variability with species, geography and season; extraction standardization lacking
Fungal biosynthesis	Fungal cultures/filtrates (e.g., *Trichoderma reesei*, *Neurospora crassa*)	Extracellular enzymes and secreted metabolites act as reducing/capping/stabilizing agents	Enables complex Mult metallic nanoparticles; high enzyme secretion capacity	Slower kinetics; strain culturing and maintenance complexity at scale
Bacterial / yeast biosynthesis	Bacterial or yeast cell cultures	NADH/NADPH-dependent enzymatic reduction; cell-surface functional-group interactions	Compatible with bioreactor scale-up; useful for agricultural and remediation nanoparticles	Intracellular synthesis can cause polydispersity; purification adds complexity.
Algal / cyanobacterial synthesis	Macroalgal or microalgal biomass, cyanobacteria	Polysaccharides and proteins mediate reduction and stabilization	Scalable biomass source; demonstrated broad-spectrum antimicrobial nanoparticles	Species- and growth-condition-dependent yield; downstream processing needs optimization
Green-solvent-mediated (DES / ionic liquids)	Choline chloride–urea and related deep eutectic solvent systems	DES act as tunable reaction media and, in some cases, as reducing/capping agents	Low toxicity, often biodegradable and recyclable; lower-temperature/pressure operation	Viscosity can limit mass transfer; recyclability and cost at scale still being validated

Sustainable Nanomanufacturing

While modification of materials to match the requirements of green nanotechnology is one aspect, the process of its creation (reaction energy input, purification, scale-up, and quality control) itself must be reengineered to be resource-efficient in engineering and operation, and to keep the process on track with minimum resource consumption. The applications of green-chemistry design principles to nanofabrication, energy-efficient and atom-efficient process design strategies are reviewed, and the increasing contribution of AI and ML in the field of sustainable nanomanufacturing is stressed [6].

Green chemistry principles in nanofabrication

The twelve principles of green chemistry that were expressed by Anastas and Warner, including waste avoidance, atom economy, safer solvents, energy efficiency, renewable feedstocks, etc., serve as a conceptual framework for sustainable nanomanufacturing. Considering the twelve principles, some groups have recently suggested standardized benchmarking frameworks (such as sustainability scalability reproducibility (SUS-SCA-REP) metrics) that

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will allow comparing the achievements of green synthesis studies, which were previously reported using inconsistent or inapplicable measures of sustainability [8,49,50].

The holistic review of sustainable synthesis pathways highlights case studies of using agricultural residues, biodegradable waste materials or renewable polymers as low-cost feedstock for the synthesis of nanomaterials, and cautions that the '"green"' producing recipe itself is only the first stage of the process and that the overall life cycle of the synthesis process should be assessed accordingly (energy costs for drying, calcination and purification of the product) [6,7,9,46].

Energy- and atom-efficient process design

There is life-cycle evidence that the energy use during reaction (e.g., heating, milling, sonication) and removing various impurities and drying the product downstream can be the main driver of the environmental impact, or even more significant than the choice of precursors. While tonings can overcome the use of highly refined chemical feedstocks through e.g. hydrothermal synthesis, they can also require constant input of energy to keep the process at high pressure and high temperatures, and may not be unambiguously 'green' in all e.g. environmental impact categories; trade-offs must be assessed at a holistic level [2,3,51].

Process-intensification strategies for nanomanufacturing are: Continuous Flow Microreactor Synthesis, which involves modifying the heat and mass transfer compared to batch reactors; electrochemical/electrodeposition routes (these are ambient temperature processes); and DESs and other reagent systems that can be reused in multiple synthesis cycles. The recycling process of the nanomaterial-based adsorbents, such as thermal treatment, chemical washing, and electrochemical reaction, also prolongs the functional life and decreases the environmental footprint per adsorbent for every unit of pollutant eliminated, especially in environmental remediation applications [30,33,51,52].

Artificial intelligence and machine learning (ML) in sustainable nanomanufacturing

The use of data-driven ML is growing in the field of accelerating the discovery, design, and process optimization of nanomaterials with a clear and explicit focus on sustainability goals. Potential applications reported recently in the literature include the use of ML algorithms to direct biomineralization processes for improved predictive control of the properties of nanoparticles and the use of AI-based nanocomposite design tools for clean energy carbon capture, utilization, and storage (CCUS) applications that rely on the use of nanoparticles [53-56].

In addition to synthesis optimization, ML is also increasingly being used to create a digitalized mapping of the data that characterize nanomaterials with the process parameters, supporting 'safe-and-green-by-design' manufacturing that includes environmental and health impacts as requirements from the earliest design phase, and for speeding up the development of formulae of green solvents for this application, as for DES-based Li-ion battery cathode recycling described in Section Green solvents: DES and ionic liquids. Most general publications of AI in the context of sustainable manufacturing highlight energy optimization, predictive maintenance, waste reduction and implementation of the circular economy as key application areas where AI has the potential to impact net-zero and Sustainable Development Goal targets in industrial sectors, such as nanomanufacturing [37,57,58].

One particular and increasingly mentioned case is using AI explicitly for sustainability aspects, such as enhancing synthesis routes and formulations for nanomaterials to maximize combined performance and environmental impact goals, instead of just maximizing performance [59].

Applications advancing net-zero and resource-efficiency goals

There are already sustainable (green) nanomaterial products being used in different parts of the economy where they have immediate relevance to the net-zero transitions: renewable energy and storage, carbon capture, water treatment and sustainable agriculture. Here we take a quick look at some of the most recent applications and the performance and sustainability benefits associated with them (Figure 2).

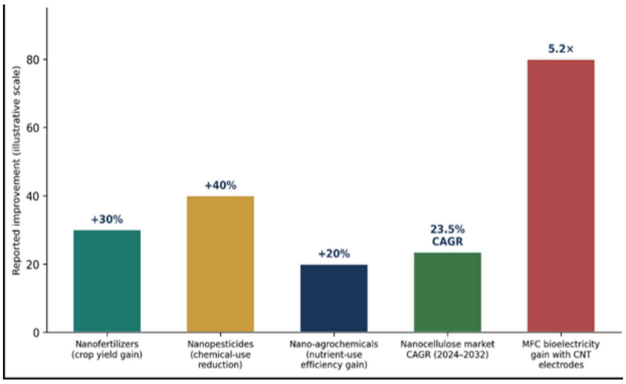

Figure 2. Selected literature-reported performance gains from sustainable nanotechnology applications relevant to net-zero and resource-efficiency goals.

Renewable energy: Solar cells, batteries, and supercapacitors

In PV systems, the ability of nanomaterials (carbon nanotubes, graphene, metal or metal-oxide nanoparticles and quantum dots) to increase light absorption, charge transport and power-conversion efficiency enhances system effectiveness in PV technologies, as well as electrical conduction and weight reduction in the electrodes of batteries and supercapacitors. In tandem cells with a perovskite/silicon combination, for which results of up to 35% have been realized in the laboratory, the challenge now lies in the interface contact, whereas the potential for hot-carrier extraction is nearing 66% in perovskite-based cells. Quantum-dot solar cells with size-tunable bandgaps have efficiencies of near 18% in the laboratory and have a theoretical limit due to hot-carrier extraction [60-65].

Sustainability aspects are increasingly embedded in the design of the devices: 'safer-by-design' devices with engineered aluminium-oxide nanoparticles in perovskite solar cells have been found to simultaneously yield performance and reduced leakage of hazardous iodine, thereby offering a way to balance safety and performance without compromising goals. In energy storage, nanostructured electrodes and solid-state electrolytes offer energy and power density, boost cyclability and provide batteries and supercapacitors with enhanced safety, including key features to enable the penetration of variable renewable energy and electrification of transport and industry. Despite this, reviews go on to warn of the high energy and chemicals required in producing the large-scale quantities of nanomaterials needed for energy-related applications, and the difficulties of recycling nano-enhanced solar cells and batteries, which are still not well-solved issues of circularity [65-75].

Carbon capture, utilization, and storage

The porous nanomaterials, particularly metal-organic frameworks (MOFs), porous carbons and designed polymer membranes, offer the high surface area, tunable pore chemistry, and specific adsorption capabilities that are necessary to achieve CO_2 capture from point sources and, more recently, increasingly developed direct air capture. For instance, MOF-210 shows near 54.5 mmol g-1 CO_2 adsorption at 50 bar, while the HKUST-1 and MOF-74 family of open metal site-based frameworks exhibit high low-pressure CO_2 adsorption, attributed to direct chemical interaction between the CO_2 molecules and the unsaturated metal centres [76-79].

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A general drawback of single-component MOFs is their mechanical fragility, which promotes or drives the development of composite approaches that combine MOFs with "green" nanostructures (nanocelluloses, for instance), enabling high porosity along with mechanical strength, and which directly relates to the carbon capture and green materials applications described in this review. Besides adsorption, a variety of nanostructured catalysts are in development for CO_2 hydrogenation and for photocatalytic and electrocatalytic CO_2 reduction, and organic magnetic nanoparticles have been reported to catalyze CO_2 capture coupled with hydrogen production, where the carbon-capture value chain meets the green-hydrogen value chain [45,80,81].

Water treatment and environmental remediation

Nano adsorbents, nano catalysts and membrane-integrated nanoparticles comprising green and biologically synthesized nanomaterials are used for the removal of dyes, heavy metals, and organic pollutants from industrial and municipal wastewater. The use of plant extracts, fungi, bacteria and algae to synthesize these nanomaterials also means they are often claimed to provide higher environmental compatibility than nano adsorbents that are synthesized using hazardous chemical reagents and possess acceptable or even better pollutant removal capacity due to their high surface-to-volume ratio and surface chemistry that can be controlled to suit the needs of the remediation application [82-87].

Bio-inspired, green-synthesized nanoparticle-based membrane technologies have enhanced the hydrophilicity, antifouling performance and mechanical strength for water purification and desalination. The specific surface area of the nanomaterials is responsible for enhanced microbial adhesion and direct electron transfer (DET), which led to bioelectricity production gains of up to 5.2-fold and also to increased coulombic efficiency in microbial fuel cells (MFCs) with carbon nanotube, g-C_3N_4, or reduced-graphene-oxide electrodes when compared with control cells. However, reviews warn that there are still major challenges for the full-scale use of green nanomaterials in municipal and industrial water treatment, namely scalability, production cost, and lack of universally accepted regulations for green nanomaterials [87-89].

Sustainable agriculture: Nano fertilizers, nano pesticides, and nano sensors

Inadequacy of conventional agrochemicals in terms of their low efficiency, from which only an estimated 1-25% of applied pesticides reach its target pests, is mitigated by agricultural nanotechnology, which includes the use of nano pesticides, nano sensors, nano fertilizers, and nano biochar. The targeted delivery and controlled release of nano formulations, along with their greater environmental stability, show potential for up to a 30% yield increase in the field with the application of nano fertilizers, and up to a 40% reduction in the quantity of chemicals applied with nano pesticides, with greater environmental stability and reduced contamination (Figure 3) [90-94].

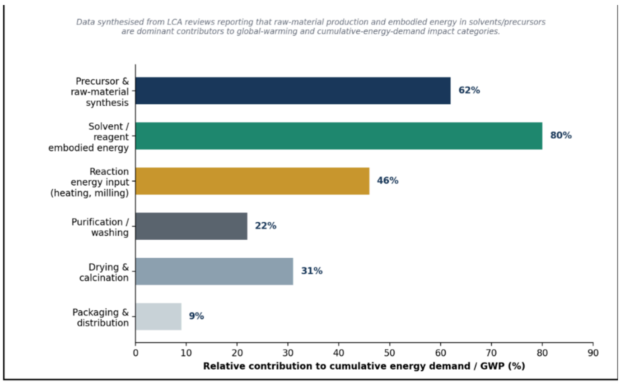

Figure 3. Representative environmental hotspots identified across life-cycle assessment (LCA) studies of engineered-nanomaterial production.

On average, the various formulations studied will improve nutrient-use efficiency by about 20%, which will help achieve United Nations Sustainable Development Goal 2 (Zero Hunger) and others related to climate change by lowering excess fertilizer use and runoff, thereby reducing the greenhouse-gas and water footprints. Some first-generation engineered nano-agrochemicals have environmental persistence and toxicity. Nano fertilizers, nano pesticides and nano pesticides made from green methods like plant-, fungal- and algal-mediated synthesis, as mentioned in Green materials for nanotechnology, further decrease the toxicity and environmental persistence. However, today, nano-agrochemicals account for less than 1% of the global agrochemical market, due to cost, regulatory uncertainty and the need for additional field-scale validation before large-scale adoption (Table 2) [92,95-100].

Table 2. Representative applications of green and sustainable nanomaterials across net-zero-relevant sectors.

Sector	Representative nanomaterial classes	Function/mechanism	Reported benefit
Solar photovoltaics	Perovskite nanocrystals, quantum dots, Al_2O_3 safe-by-design (SbD) coatings	Enhanced light trapping, charge transport and anti-reflection	Tandem-cell efficiencies approaching 35%; safer-by-design coatings reduce iodine leakage while maintaining performance
Batteries & supercapacitors	Graphene, carbon nanotubes, nanostructured electrodes/electrolytes	Improved conductivity, energy/power density and cycling stability	Faster charging, higher capacitance and longer cycle life relative to conventional electrodes
Carbon capture, utilization & storage	MOFs, nanocellulose–MOF composites, porous carbons	High surface area and tunable pore chemistry for CO_2 adsorption/reduction	MOF-210 CO_2 uptake ≈54.5 mmol g^{-1} at 50 bar; nanocellulose improves mechanical robustness of MOF composites
Water treatment	Green-synthesized metal/metal-oxide nanoparticles, CNT/graphene-oxide electrodes	Adsorption, photocatalytic degradation, antifouling membranes, microbial fuel cell electrodes	Up to 5.2× bioelectricity generation and >2× coulombic efficiency with CNT-modified MFC electrodes
Sustainable agriculture	Nano fertilizers, nano pesticides, nano biochar, nano sensors	Targeted, controlled-release nutrient/pesticide delivery; real-time soil/plant monitoring	Up to +30% crop yield, up to −40% chemical pesticide use, ≈+20% nutrient-use efficiency

Environmental health and safety: Nanotoxicology and safe-by-design

Environmental-health-and-safety (EHS) properties of nanomaterials

Any serious net-zero nanotechnology agenda should be based on a

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strict assessment of (EHS) properties; replacing a hazardous chemical reagent with a plant extract does not mean that the resulting nanomaterial will be harmless to humans and ecosystems. These properties can trigger oxidative stress, inflammatory response and altered biodistribution, regardless of the "greenness" of the synthesis pathway employed to make nanomaterials, and are reflected by their high surface area to volume ratio, tunable reactivity and capacity to translocate beyond their initial pathway of exposure [101-103].

Safe-by-design paradigm and aquatic nanotoxicology

SbD paradigm seeks to include hazard-reduction strategies early in the development of nanomaterials, instead of as an end-of-pipe regulatory challenge. Data on aquatic nanotoxicology for silver nanoparticles, one of the most studied engineered nanotechnology products, are used for illustrative purposes to demonstrate how the ecotoxicological impacts on freshwater and marine organisms vary as a function of the physicochemical properties of the nanomaterials, including their size, shape, surface coating, aggregation state, etc., and to provide a template for other classes of engineered nanomaterials [104,105].

Regulatory Evolution and harmonization

The regulation of nanomaterials has evolved in parallel with the research basis: Since 2000, international bodies such as the OECD Working Party on Manufactured Nanomaterials have established test guidelines for nanomaterials, including physicochemical characterization, exposure assessment and hazard identification, which were applied to nanomaterials in the EU's REACH regulation. Despite this, after 25 years of nanotechnology research and regulation, there is still a lack of regulatory harmonization across jurisdictions, and a recent assessment of the rate at which new nano formulations are being developed, particularly those made using green synthesis methods as described in this review, indicates that the supply of available, comparable toxicological data is falling behind [106].

Mitigation strategies and risk-assessment approaches

Methods proposed to mitigate nanotoxicity found in the literature include modifications, functionalization of surfaces to minimize generation of reactive-oxidation species, multi-tiered risk assessment that utilizes in vitro, in vivo, and in silico organs-on-chips approaches, and flexible regulation that will mature in step with the technology. Ecologically relevant, chronic-exposure test protocols have become more popular and are favored over acute-exposure assays, because real-world exposure to nanomaterials from consumer products, from agriculture, and at the end of life is low dose and long duration [105,107,108].

Life cycle assessment (LCA) and carbon footprint of nanomaterials

LCA is the primary methodological tool to measure LCA benefits, which are the absolute reduction in environmental impact when compared to a non-green synthesis route or sustainable manufacturing process at the full material life cycle, integrated over the raw-material extraction stage, synthesis, use, and end-of-life of the product [109].

Critical reviews on LCA studies focusing on nanotechnology (specifically the pooled cradle-to-gate datasets compiled in reference [2,3]) show that the energy-intensive stages of synthesis and purification account for around 62% of the contribution to GWP and 80% to CE-D impact categories across the studies reviewed therein, respectively. It directly affects the green-materials strategies discussed in Section 2: Using a plant extract or DES as the reducing reagent in the replacement approach instead of a toxic reagent reduces the impact of toxicity but does not necessarily reduce cumulative energy demand if the energy demand for extracting the plant extract or purifying the DES is still significant, emphasizing the value of full-system LCA over single-attribute 'green' claims [2,3].

Conventional Life Cycle Analysis (LCA) suffers from a lack of end-of-life and recycling information, especially for nanomaterials, as well toxicity in the environment, especially through conventional impact-assessment approaches; many nanomaterials have not yet reached maturity, thus there is a lack of standardized LCI data; and most impact-assessment frameworks are not designed to account for the environmental life cycle of nanomaterials. Several technologies are being explored to mitigate time and skills barriers often associated with conducting comprehensive and comparable LCAs, such as the introduction of emerging digital tools including the use of LCA reports produced using a large language model (LLM) and procedure automation. LCAs' potential to be confused by selective framing and greenwashing has also been discussed in the sustainability-science literature, further underscoring the need to use transparent, peer-reviewed, and ideally, third-party verified LCA methods when assessing sustainability claims of green or circular nanomaterials. [3,109,110]

The sector-specific nuance needed is highlighted in comparative LCA case studies: for nano-enabled electronics, LCA of recyclable all-carbon thin-film transistors concludes that whether or not a nano-device is 'net positive' across all LCA impact subcategories depends on both the choice of material used and its end-of-life recyclability; for bio energy and biogas applications, LCA of nano material-assisted anaerobic digestion shows gains in LCA impact subcategory GWP, but losses in LCA impact subcategory FFDP for some feedstocks, and vice versa for others, emphasizing that no nanomaterial application qualifies as 'net positive' LCA across all impact subcategories without case-specific LCA verification (Table 3) [111-113].

Table 3. Life-cycle-assessment findings on environmental hotspots of nanomaterial production.

Life-cycle stage	Dominant impact category	Reported finding
Precursor & raw-material synthesis	Global warming potential (GWP)	Raw-material production contributes approximately 62% of GWP impact in representative LCA studies of nanomaterial manufacture.
Solvent & reagent embodied energy.	Cumulative energy demand (CED)	Embodied energy in solvents and precursors contributes approximately 80% of CED impact in representative studies.
Reaction energy input	GWP / CED	Hydrothermal and solvothermal routes require sustained high-temperature/pressure energy input, partially offsetting benefits of water-based or refined-chemical-free feedstocks.
Purification, drying & calcination	CED	Downstream thermal processing steps are frequently under-reported in LCA studies but can be significant contributors to total energy demand.

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Table 3 (continued)

Life-cycle stage	Dominant impact category	Reported finding
End of life/recycling	Resource depletion, GWP avoided-burden credit	End-of-life and recycling data remain scarce for most nanomaterials, limiting full-system LCA comparability across studies.

Circular Nanoeconomy

The circular nano economy is the application of the principles of the circular economy to the nanoscale, and encompasses the three core pillars of designing out waste, keeping materials and products in use and regenerating nature. Nanomaterials pose unique recovery issues as compared to bulk materials, and added economic benefit where underlying elements (gold, silver, platinum-group metals, and rare-earth elements) are economically desirable or supply-restricted (Figure 4) [114,115].

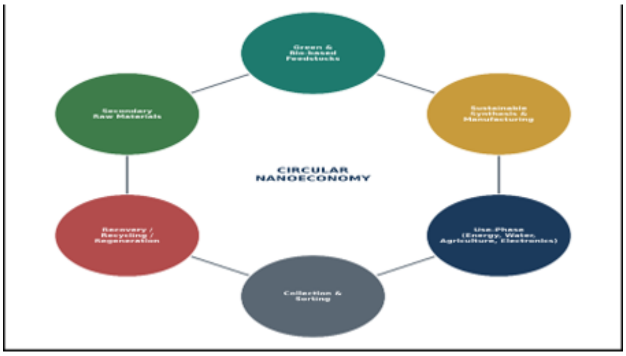

Figure 4. Idealized material-flow loop of a circular nano economy, from green feedstocks through use, recovery, and re-entry as secondary raw materials.

End-of-life recovery, recycling, and regeneration

Materials in a circular economy can follow either of two "cycles": a biological cycle, where the bio-based materials decompose safely and enrich the natural systems; or a technical cycle where finite, abiotic materials are used in an efficient way, and are cycled back through remanufacturing, repairing, reuse and recycling. It is important to be aware of the ever-increasing presence of engineered nanomaterials in the supply chains of many products that play a role in almost every aspect of society, thus highlighting that the uptake of engineered nanomaterials into these circular flows of resources is not just a sustainability issue, but an important step towards the general evolution of material circularity [116].

End-of-life management strategies for carbon nanomaterials focus on electrochemical recovery methods, direct applications to conductive inks, coatings, and composite materials, and repeated functional applications by comparatively easy surface modification, annealing, and doping to keep the structural and electronic properties intact from end-of-life, with multiple uses for each. Covalent adaptable networks (CANs) (which include vitrimer types that can exchange associative bonds) provide reprocess ability of thermoset nanocomposites, which heretofore have been problematic to recycle because cross-linking is irreversible; mechanical recycling via re-extrusion is even more readily scalable, but a less valuable mechanism [117,118].

Recovery of metallic nanoparticles from secondary sources such as electronic waste, spent catalysts and industrial process residues is a particularly attractive circular pathway since the intrinsic value of precious and critical metals is high. Taking just one example, printed circuit board wastes have significantly higher gold concentrations (around 200-250 g per tonne) than a normal mined ore (below 10 g per tonne) and, therefore, are an economically advantageous secondary feedstock for synthesis of nanoparticles, if appropriate recovery and purification technologies can be implemented at the required scale and quality. Mining tailings are also an untapped and potentially abundant source of sustainable nanomaterials as part of environmental liability cleanups and supply chains' resistance against natural disasters [119-121].

Critical raw materials and supply-chain resilience

Several of these high-performance nanomaterials rely on critical raw materials (CRMs), rare earth materials, cobalt, lithium, and platinum group metals, many of which are concentrated in a single country of origin and, for some, with a heavy environmental and social footprint, including the need for more than 1,000 times more freshwater to harvest lithium than it took to harvest iron. Going forward, as detailed in the fourth section, demand for minerals could increase by almost 3 times by 2030 and reach ~40 million tonnes a year at about the same time under a net zero emissions scenario, which could create pressure for supply shortages on the same minerals driving many of the net zero technologies enabled by nanomaterials detailed in Section 4 [122-125].

Interventions at the policy level have picked up speed since 2023–2024. The European Union's recently approved NZIA enacted in 2024 aims to supply at least 40% of all the EU's annual clean-energy-technology deployment needs from the domestic market by 2030; the complementary CRMA) has laid down extraction, processing, and recycling targets for strategic materials and explicitly includes recycling and material substitutions as complementing primary supply from geopolitically diversified sources. The EU Battery Regulation also introduces requirements for lifecycle management which are aimed at ensuring the Circular economy, directly applicable to the battery supply chain relevant to the nanomaterial-based battery technology introduced in Section Renewable energy: Solar cells, batteries, and supercapacitors [126-129].

There are similar examples at the national and multilateral level: at national level studies of material-flow analysis are being complemented with critical-material assessments to determine the degree of crisis in the supply of materials such as batteries and clean energy technologies, and how the criticality of those resources can be reduced through recycling or material substitution; at multilateral level, OECD analysis shows that identifying the criticality of materials in the supply chain is not a purely market-driven endeavour, but is also a question of economic security, warranting international and coordinated policy response [122,130].

Policy, standardization, and business-model innovation

The development of circular nanoeconomy also requires more definitions and indicators for 'circular' nanomaterials, and design for disassembly and design for recyclability guidelines specific to nano-enabled products; and business-model innovation, including implementation of material-as-a-service, and take-back schemes. Stakeholder analyses of EU regulatory landscapes point to policy fragmentation and regulatory complexity at the European level across the Green Deal Industrial Plan, NZIA, CRMA and Battery Regulation respectively, creating an opportunity to build up industry as well as confusion about the practical governance challenge of linking up and articulating, at an EU level, the ambition of a circular economy to coherent regulatory certainty in investable capacity in nanomanufacturing [116,128,129].

Many of the policy texts stress the need to pursue strategic dominance in critical, and centrally important, segments of the new nanotechnology economy, either through bringing to the shore trade or friendshoring or export controls, but then again, this does not match the transnational nature of effective, low-carbon critical-material supply chains now needed and of effective international nanomaterial recycling infrastructure, which these institutions ultimately

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stand to profit from Table 4 [123,125].

Table 4. Circular-economy recovery strategies by nanomaterial class.

Nanomaterial class	Recovery/recycling strategy	Secondary feedstock source	Key challenge
Precious & critical metal nanoparticles (Au, Ag, PGMs, REEs)	Hydrometallurgical/bioleaching recovery, re-synthesis into new nanoparticles	Waste printed circuit boards (≈200–250 g Au per tonne vs. <10 g per tonne in typical ore); mining tailings	Purity and scale-up of recovery processes; cost-competitiveness with primary extraction
Graphene & carbon nanotubes	Electrochemical exfoliation/recovery, direct reuse, functional regeneration (annealing, doping)	End-of-life composites, conductive inks, spent electrodes	Preserving structural/electronic properties across multiple recovery cycles
Thermoset polymer nanocomposites	Covalent adaptable networks (vitrimers), mechanical re-extrusion	End-of-life composite components	Balancing reprocessability with retained mechanical performance
Metal-oxide nanomaterials	Recovery from red mud, slag, rusted wires, discarded capacitors	Metal-industry and electronic waste streams	Variable feedstock composition complicates consistent nanomaterial quality
Nano-enabled batteries & solar cells	Emerging chemical/mechanical recycling routes (still largely pre-commercial)	Spent lithium-ion cells, end-of-life PV panels	Recycling infrastructure and economic incentives remain underdeveloped relative to production growth.

Challenges and Future Perspectives

While remarkable strides have been made with green materials, sustainable manufacturing processes, and circular-economy approaches, there are still fundamental barriers to placing sustainable nanotechnology into industrial practice in order to achieve a net-zero operational state.

Despite the advances made, standardization and reproducibility still play a key role as obstacles for plant-, microbial-, and algal-mediated synthesis; batch-to-batch variation in phytochemical and metabolic composition of the biological source is a significant challenge for regulatory characterization and industrial quality control regarding standardization and reproducibility in terms of size, shape, yield, etc. of the nanoparticles produced. Proposed benchmarking frameworks (such as SUS-SCA-REP) make a good head start to the notion of comparable and transparent sustainability reporting, but are yet not widely embraced by the industry [21,24,50].

Scalability and cost are recurring challenges: a few synthesis pathways shown at lab level, such as microbial or algal biosynthesis, are far from being proven at the commercial scale for the volumes of production required for commercialization; while LCA data suggest that some green synthesis pathways may not yield a lower life cycle energy demand than conventional synthesis when considering cumulative energy demand from extraction, purification, and drying. This will not just be achieved through 'qualitative' 'green' framing only; it will involve further optimization of processes, guided by LCA [3,25].

Going forward, regulatory harmonization among jurisdictions continues to be incomplete, including between the EU nanomaterial framework based on REACH, the U.S. regulatory framework and nascent frameworks in Asia, contributing to regulatory complexity for companies involved in the manufacturing of nanomaterials across multiple jurisdictions and the slowdown of the diffusion of innovations for SbD and circular nanomaterials to markets. Another barrier, related to data availability, is the lack of standard, comparable life cycle inventory and toxicological data for many novel green-synthesized nanomaterials, which constrain the reliability of comparing sustainability aspects in the literature cited in this article [106].

The growth of production of nanomaterials is significantly outpacing end-of-life recovery, especially for batteries, solar cells, and composite materials, and end-of-life technology is not fully developed, particularly for collecting and recycling the ever-increasing number of materials at high volume using high-value applications like nano-enabled batteries. Last but not least, critical-raw-material supply-chain resilience will depend on long-term and international investment in the recycling of materials, secondary-resource recovery from e-waste and mining tailings, and research on material replacement for several materials that will support critical net-zero technologies, given that the demand for some of these materials is predicted to rise significantly faster than diversified primary supply can keep up with [71,75,122,124].

As revealed in the possible combinations of knowledge and learning above, the future of nanotechnology seems promising toward a truly "net zero compliant" industry, with the possibility of coordinated research, industry, and policy activities to address standardization, scale-up, and regulatory-harmonization challenges.

Conclusion

This is not the only factor that can define the impact of functional performance nanomaterials towards a net-zero future; the ability to produce, use and process them in a circular, decarbonized system is at least as important. The key and main conclusion of this review is that green synthesis, sustainable manufacturing and circular recovery are not connected by distinct and separate pathways; they are interconnected, and it is premature considering the different rates of advancement of the three fields, whether or not each other will be hindered. The development of synthesis from green materials is achieving the fastest results; routes for biosynthesis and the use of green solvents have already proven to be viable substitutes for toxic precursors at bench and pilot plant scale. AI/ML is helping to optimize processes, with sustainable nanomanufacturing putting up some catching-up time, though the ability to design atoms-efficient processes for nanomanufacturing is limited by the absence of a common set of metrics for measuring and comparing atoms-efficient "green routes" to traditional routes in a meaningful way. Recovery technologies at end-of-pipe are less well-integrated in the circular nano economy: technologies do exist but are not aligned with upstream design choices, and nanomaterials are presently mostly designed without consideration of their end-of-pipe recyclability or recoverability.

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The review's most important additional value is the fact that optimizing each pillar separately for deployable, sustainable nanotechnology is not enough; optimizing each pillar by designing materials from the synthesis onward to enable recovery and decarbonization is required. What's needed is a reliable, standardized method to calculate and map the life cycle of a product, including toxicological screening, as core components from the outset of its development, while maintaining a regulatory toolbox with incentives to encourage this integration instead of isolating all aspects of its lifecycle as distinct regulatory fields after synthesis, manufacture, or at the end of its life. In this regard, nanotechnology will not just benefit the overall shift to a net-zero, circular economy, but could also be a design-stage lever to set this transition in motion; provided innovation makes the step not only from optimization of each pillar to a truly integrated design.

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T. Vedavathi: Contributed to the literature review and data collection, developed the manuscript structure and graphical content, and prepared the original draft.

G. Prathibha: Assisted with the literature survey and critical review of the manuscript.

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