Green Synthesis in Materials Science: Converging Bio-Routes, Deep Eutectic Solvents, Mechanochemistry, Flow, Microwave, and $scCO_2$ toward Low-Impact Functional Materials

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Abstract

Green synthesis adapts the 12 principles of green chemistry to design material fabrication routes that minimize hazardous substances, enhance atom economy, and improve energy efficiency from lab to industrial scale. Bio-mediated synthesis using plant extracts and other biogenic agents provides benign reducing and stabilizing environments for metals and oxides with utility in catalysis, energy, and biomedicine. Deep eutectic solvents (DES) offer tunable, low-volatility media that act simultaneously as solvents, templates, and functionalization agents to control morphology and surface chemistry. Process-intensified strategies—including solvent-minimal mechanochemistry, continuous-flow microreactors, and microwave assistance—lower solvent footprints, shorten cycle times, and increase selectivity and scalability. Supercritical CO_2 enables recyclable, low-toxicity processing that improves transport, phase behavior, and product quality in polymer, inorganic, and electrode material syntheses. Sustainability quantification via life-cycle assessment complements green metrics by comparing energy use, emissions, and resource burdens across raw materials, processing, use, and end-of-life. This review synthesizes advances at the chemistry–physics interface and outlines opportunities to integrate DES, mechanochemistry, flow, microwaves, and $scCO_2$ with bio-routes for low-impact functional materials across energy, environmental remediation, and healthcare.

Keywords: Deep eutectic solvents, Mechanochemistry, Plant-mediated nanoparticle synthesis, Supercritical CO_2 processing, Flow microreactors.

Introduction

Green synthesis redefines materials design towards prevention, safer solvents, energy efficiency, catalysis, and end of life design to minimize environmental and human health costs without compromising performance or scalability. These principles have catalysed a transition from hazardous, solvent intensive pathways to safer platforms, such as bio mediated synthesis, DES, solvent free mechanochemistry, and intensified flow/microwave processes. The initial concepts are based on Anastas–Warner, and later developed across disciplines. Interdisciplinary collaboration in chemistry–physics leverages transport, thermodynamics, reaction engineering, and interfacial phenomena towards greener routes to develop functional nanomaterials, thin films, and porous architectures.

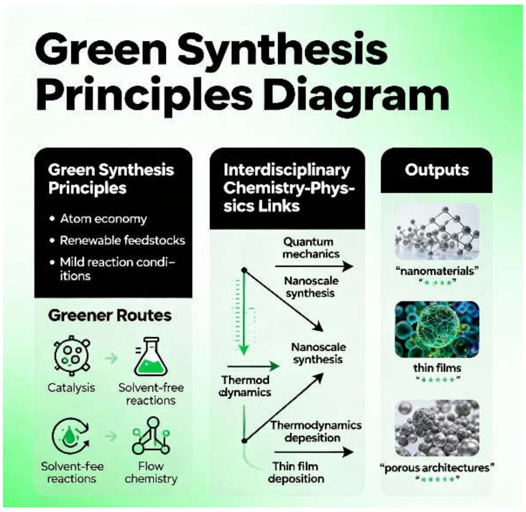

Fig.1. Interdisciplinary Green Synthesis Linking Chemistry–Physics to High-Performance Nanomaterials and Thin Films.

Principles and metrics

The 12 principles highlight atom economy, less hazardous syntheses, safer solvents, energy efficiency, renewable feedstocks, catalysis, and design for degradation, offering a checklist for greener routes and scale up decisions. This is complemented by quantitative metrics and life cycle assessment that increasingly compare conventional versus green pathways on energy demand, emissions, and resource use to avoid burden shifting across unit operations and stages. Historical analyses of green chemistry underscore multidimensional impacts, from safer lab protocols to industrial adoption in solvents and continuous processing.

Bio-mediated synthesis

Plant extracts, microbes, and biopolymers provide reducing and capping agents—flavonoids, phenolics, proteins, and polysaccharides—that facilitate the aqueous, low-temperature preparation of metal and metal oxide nanoparticles of tailored size and morphology. Recent reviews break down mechanistic influences (pH, phytochemical composition, ionic strength) on nucleation and growth, elucidating the manner in which bio actives govern kinetics and surface passivation across Ag, Au, ZnO, and TiO_2 systems. Biomedical and environmental applications benefit from biogenic surface chemistries that can improve colloidal stability and biocompatibility, though reproducibility and standardization remain scale up challenges.

Deep eutectic solvents (DES)

DES offer low volatility, engineered media serving as a solvent, template, and dopant for morphology control, crystal growth modulation, as well as surface functionalization in inorganic and hybrid materials. Reviews highlight the tunability of DES via hydrogen bond donors/acceptors, viscosity–diffusivity balances, and coordination environments that steer nanostructure formation and porosity. Emerging studies detail DES processed adsorbents, catalysts, and energy materials, with ongoing work on viscosity management, water tolerance, and recycling protocols for circular use.

Mechanochemistry

Mechanochemistry provides solvent-free or solvent minimal transformations via milling or twin screw extrusion, decreasing E factors while enabling solid state pathways inaccessible in solution. Recent progress has been made in the areas of inorganic frameworks, metal–organic hybrids and selective bond formation reactions, while improved kinetics were observed through localized thermal and pressure spikes and in situ monitoring. Reviews emphasize alignment with green principles through solvent elimination, energy reduction, and facile scale up, while noting needs in process control, real time analytics, and broader materials classes.

Flow chemistry and microreactors

Continuous flow and micro reaction technologies, which facilitate heat/mass transfer, narrow residence time distributions, and increased mixing efficiency improve selectivity and safety, and allow for accurate kinetic manipulation. The benefits can also be used in nanomaterial synthesis, photocatalytic coatings, and reactive crystallization with scalable footprints and in line analytics to reduce waste. We emphasize sustainable benefits of modularity, lowered solvent inventories, and higher scale-up efficiency relative to batch in the case studies and field guides.

Microwave-assisted routes

Microwave heating provides rapid, volumetric energy input that shortens reaction times and refines nucleation–growth windows for size controlled nanomaterials and carbon dots under greener conditions. Recent demonstrations include neem leaf-mediated graphene quantum dots and plant assisted metal oxide nanoparticles with reduced by products and lower thermal budgets. Methodological reviews and applications point to lower energy consumption and improved crystallinity, with attention to uniformity, penetration depth, and reactor scalability.

Supercritical CO_2 ($scCO_2$) platforms

Supercritical CO_2 gives a tunable density, diffusivity and solvent power for greener reactions, particle formation, impregnation and polymer processing and easy post process separation. Materials applications: electrode synthesis/modification, porous architectures, and catalysis with improved mass transport and reduced solvent residues. Safety, recyclability, hybridization with flow platforms to combine green solvent benefits and intensified operation are highlighted in overviews of equipment and process design.

Sustainability assessment and LCA

Comparison of green versus conventional LCAs of traditional routes discloses trade-offs in energy, emissions, and precursors, driving system-level optimization beyond one-dimensional benchmarks such as yield or E factor. Recent development of LCSA in bio derived materials and porous frameworks integrates environmental, economic and social aspects for decision support. From heritage science to advanced materials, life cycle approach is prioritizing durability, reusability, and end-of-life as key to green synthesis assertions.

Applications across chemistry–physics

Green nano synthesis for energy materials is based on controlled interfaces, defect engineering, and scalable morphologies for catalysis, storage, and conversion under safer conditions. Environmental remediation by using biogenic and DES processed adsorbents and catalysts combines performance improvement with lower toxicity and better recyclability. Biomedicine capitalizes on greener surface chemistries and reduced residuals to enhance biocompatibility and translation potential of nanoparticulate systems.

Challenges and future directions

Reproducibility, precursor standardization, viscosity and mass transfer management in DES, and precise thermal–field control in microwaves remain active engineering challenges for scale up. Regulatory, cytotoxicity, and long term stability assessments are particularly vital for biomedical and environmental deployments of bio templated and hybrid materials. Future opportunities include hybridizing DES with mechanochemistry and flow, integrating scCO_2 with continuous platforms, and coupling real time analytics with LCA informed process optimization.

Conclusion

Green synthesis has evolved from a principle driven aspiration into an integrated toolbox in bio routes, DES, mechanochemistry, flow/microwave processing, and scCO_2 allowing for safer and scalable production of functional materials. Implementation of quantitative sustainability assessment and cross disciplinary engineering can speed the translation of these technologies into energy, environmental, and biomedical applications while minimizing life cycle burdens. These platforms are potentially integrated strategically and their architectures/interfaces could achieve tunable structures and interfaces with reduced solvents, lower energy inputs, and improved circularity for next generation materials.

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