Safer-by-Design Green-Synthesis Nanoparticles in Environmental Engineering: A Systematic Review and Educational Framework for Risk-Informed Innovation

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Abstract

Nanoparticles are increasingly integrated into environmental engineering and sustainable construction systems to enhance mechanical strength, durability, antimicrobial performance, and energy efficiency. However, conventional nanoparticle synthesis routes are often energy-intensive and associated with chemical hazards, raising concerns about occupational exposure, environmental release, and long-term public health impacts. In response, green synthesis methods and safer-by-design (SbD) frameworks have emerged as complementary strategies for reducing risk while maintaining functional performance. This paper presents a systematic review of peer-reviewed research papers published between 2015 and 2025 examining green-synthesized nanoparticles within environmental engineering applications, with emphasis on risk-informed innovation and engineering education. The review synthesizes evidence across four dimensions: synthesis pathways, environmental and health risk profiles, safe-and-sustainable-by-design frameworks, and curriculum integration models aligned with ISO 14001 environmental management principles. Findings indicate that green synthesis significantly reduces solvent toxicity, energy demand, and hazardous by-products compared to conventional methods, while SbD frameworks enable early-stage hazard mitigation through lifecycle thinking. Despite these advances, gaps persist in standardized life-cycle assessment, long-term toxicological data, and formal integration of nanomaterial safety into engineering curricula. To address these gaps, this paper proposes a structured educational framework that integrates SbD, green synthesis, and environmental governance into environmental engineering education, supporting responsible nanotechnology innovation.

Keywords: Green-Synthesized nanoparticles, environmental sustainability, sustainable construction materials, environmental governance, engineering curriculum development.

I. Introduction

Nanotechnology has become an important part of new ideas in environmental engineering. It supports a wide range of applications, from membranes for treating water and removing pollution to new building materials that are stronger and more fire-resistant [1], [2]. Nanoparticles such as titanium dioxide (TiO_2), zinc oxide (ZnO), silicon dioxide (SiO_2), and carbon-based nanomaterials are increasingly incorporated into cementitious composites, coatings, and insulation systems to improve performance while reducing material consumption [3].

Even with these advantages, worries about the effects of engineered nanomaterials on the environment and people's health at work have grown. Chemical vapor deposition, sol-gel processing, and hydrothermal synthesis are all common ways to make things, but they often need high temperatures, dangerous solvents, and dangerous precursors. This leads to greenhouse gas emissions and puts workers at risk [4], [5]. Research has shown that the size, surface chemistry, and agglomeration behavior of nanoparticles have a big effect on how toxic they are, which makes it harder to manage risk later [6].

In response, green synthesis methods have become more popular because they are better for the environment. These methods use plant extracts, microorganisms, and biogenic waste streams as reducing and stabilizing agents. This makes it possible to make nanoparticles under milder conditions with less chemical burden [7], [8]. Concurrently, safer-by-design and safe-and-sustainable-by-design frameworks have emerged to guide the intentional integration of safety, sustainability, and functionality at the earliest stages of material development [9], [10].

While technical and regulatory research on SbD nanomaterials has expanded, engineering education has lagged in systematically integrating these concepts into curricula. Accreditation and sustainability initiatives are increasingly demanding that engineers exhibit proficiency in risk assessment, life-cycle analysis, and environmental governance; however, education regarding nanomaterial safety continues to be disjointed [11], [12]. ISO 14001 environmental management systems offer a globally acknowledged framework for integrating sustainability and risk management into organizational practices, presenting a valuable foundation for curriculum development [13].

This paper addresses this gap by synthesizing recent research papers on green-synthesized nanoparticles through the lens of safer-by-design and environmental engineering education. The objective is to evaluate technical advancements and to propose an evidence-based educational framework that equips future engineers to participate in risk-informed nanotechnology innovation.

II. Conceptual Foundations: Safer-by-Design and Green Nanomaterials

A. Green Synthesis of Nanoparticles

Green synthesis is a way to make nanoparticles that uses less harmful chemicals, less energy, and more renewable feedstocks during the whole process [7]. Plant-mediated synthesis, for example, uses phytochemicals such as flavonoids and phenolics to reduce metal salts into nanoparticles while simultaneously acting as capping agents [8]. These processes work at lower temperatures and pressures than traditional methods, which greatly reduces their impact on the environment [14].

Numerous studies indicate that green-synthesized ZnO and TiO_2 nanoparticles display similar antimicrobial and photocatalytic efficacy as their chemically synthesized equivalents, while exhibiting lower ecotoxicity in aquatic testing environments [15], [16]. However, differences in the size distribution of particles and the ability to reproduce results from one batch to the next are still problems for large-scale use [17].

B. Safer-by-Design and Safe-and-Sustainable-by-Design Frameworks

Safer-by-design frameworks focus on finding hazards before they happen, reducing exposure, and lowering risk throughout the life cycle of a material instead of after it has been deployed [9]. The European Commission’s SSbD framework extends this concept by explicitly integrating environmental sustainability metrics alongside safety performance [10].

Recent research has implemented SbD through tiered assessment frameworks that evaluate materials in the initial phases of innovation with basic indicators prior to progressing to comprehensive toxicological and exposure assessments [18]. AdMaCat and other design-phase tools let you compare nano-enabled materials based on environmental, safety, and performance criteria. This helps you make smart choices about which materials to use [19]. AdMaCat is the use of advanced materials classification.

These frameworks are especially useful for engineers across disciplines, particularly those engaged in materials development, manufacturing, and systems design [6], [20]. Environmental engineering programs are a good place to start learning about SbD because they already focus on exposure pathways and environmental fate. However, limiting implementation to this field would greatly limit its impact. Chemical, materials, and mechanical engineers often make decisions about how to design and make nanoparticles. To change these decisions, the curriculum needs to be more integrated so that it can influence upstream design choices where risk reduction is most effective. Thus, embedding SbD principles within both research and education is essential to ensure that sustainability gains are not offset by unintended health or ecological consequences.

III. Systematic Review Methodology

A. Review design and reporting standard

This systematic review adhered to the PRISMA 2020 reporting guidelines to ensure transparent documentation of search, screening, eligibility decisions, and synthesis procedures [11], facilitated by PRISMA's checklist and flow diagram shown in Figure 1 [12]. The review aimed to amalgamate (i) eco-friendly synthesis pathways for nanoparticles pertinent to environmental engineering and sustainable construction, (ii) safer-by-design (SbD) and safe-and-sustainable-by-design (SSbD) methodologies, and (iii) governance and standards associated with risk-informed innovation, encompassing EU SSbD assessment guidance and occupational risk standards [13]–[16].

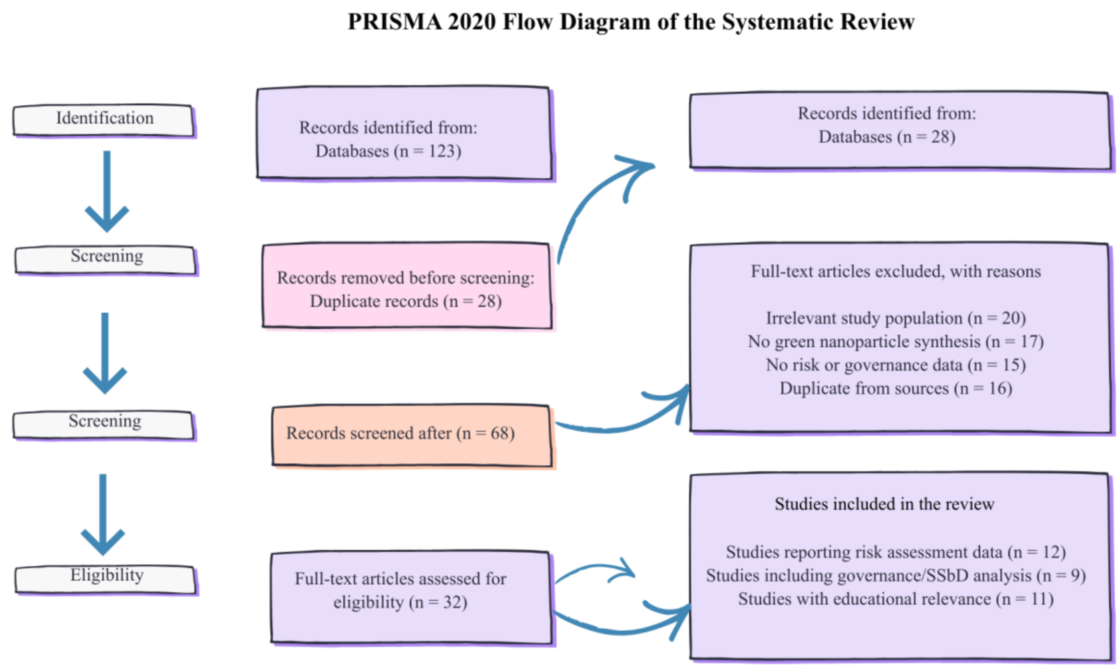

Figure 1: PRISMA 2020 Flow Diagram of the Systematic Review

B. Information sources and search strategy

The search plan focused on major bibliographic databases that are often used for environmental engineering and nanomaterials research (Scopus and Web of Science) and is supported by discipline-relevant indexing sources when necessary (PubMed for occupational exposure and toxicology). This was done to make sure that peer-reviewed research papers from 2015 to now were included. Following PRISMA 2020's advice to fully document information sources and search strings [11], [12].

Search strings were structured using Boolean logic across four concept blocks:

1. **Green synthesis**: "green synthesis" OR biosynthesis OR "plant-mediated" OR "biogenic."
2. **Nanoparticles/materials**: nanoparticle* OR nanomaterial* OR "metal oxide" OR ZnO OR TiO_2 OR SiO_2
3. **Environmental engineering/construction**: "environmental engineering" OR "remediation" OR "water treatment" OR "construction materials" OR cement* OR coating* OR "insulation."

4. **Risk and governance**: “safer-by-design” OR “safe-by-design” OR SSbD OR “life cycle assessment” OR LCA OR exposure OR release OR “ISO/TR 13121.”

A governance sub-search is conducted in parallel using official and peer-reviewed sources for SSbD and international nano-safety frameworks (EU Commission recommendation and JRC SSbD technical report) [13], [14].

C. Eligibility criteria

Inclusion criteria

- Peer-reviewed journal articles and conference proceedings (2015–present) with demonstrable relevance to:
  - green/bio-based nanoparticle synthesis and/or
  - SbD/SSbD methods applied to nanomaterials and/or
  - occupational/environmental exposure, release, or lifecycle assessment for nano-enabled materials and/or
  - governance frameworks and standards guiding safe, sustainable innovation.
- Publications in established, widely indexed venues (consistent with Scopus coverage norms for environmental engineering, materials science, and occupational health).

Exclusion criteria

- Non-peer-reviewed content (blogs, marketing pieces, non-archival web posts).
- Articles that mention “green” or “safe” only rhetorically without method/metrics.
- Studies without enough methodological detail to support extraction (e.g., missing synthesis conditions, characterization, or risk-relevant information).

D. Screening and selection process

Records were exported to a reference manager, deduplicated, and screened using PRISMA’s two-stage approach [11], [12]:

1. **Title/abstract screening** against eligibility criteria.
2. **Full-text screening** to confirm: (a) synthesis route, (b) nanoparticle type and application context, and (c) presence of risk-relevant evidence (hazard, exposure, release, LCA, or governance alignment).

Disagreements in eligibility decisions were resolved through consensus review, with reasons for exclusion recorded for PRISMA reporting [11].

E. Data extraction and coding framework

A structured extraction form is used to ensure consistent capture of both technical and risk-informed attributes, aligned with SSbD lifecycle thinking [13], [14]. Extracted variables include:

- **Synthesis**: feedstock (plant/microbial/waste-derived), precursors, temperature, solvents/reducing agents, yield, scalability notes.
- **Nanoparticle characteristics**: size distribution, morphology, surface chemistry/capping agents, crystallinity, stability.
- **Function/application**: environmental remediation, photocatalysis, antimicrobial coatings, cementitious enhancement, insulation/coatings.
- **Risk evidence**: hazard endpoints, exposure scenarios, release under use/aging/mechanical processing, and risk management measures.
- **Lifecycle governance mapping**: explicit alignment to SSbD assessment elements (design-stage considerations, manufacturing, use, end-of-life) [13], [14], and to risk evaluation guidance such as ISO/TR 13121 for communicating and managing nanomaterial risks under uncertainty [16].
- **Evidence quality flags**: presence of controls, reproducibility detail, standardized tests, and transparency of assumptions.

F. Synthesis approach

Given heterogeneity across nanoparticle types, synthesis routes, endpoints, and application contexts, results are synthesized using a thematic narrative synthesis. Findings were organized into:

1. synthesis-to-property trends in green routes (e.g., how capping agents and process conditions shift size/morphology),
2. risk profile evidence (hazard, exposure, release), and
3. governance trends (SSbD adoption, standardization, and gaps) [13]–[16].

IV. Results: Synthesis, Risk Profiles, and Governance Trends

A. Synthesis trends in green-synthesized nanoparticles relevant to environmental engineering

Across recent research papers reviews, green synthesis is consistently framed as reducing reliance on hazardous solvents and extreme reaction conditions while leveraging biological molecules as reducing and capping agents [17]. In the ZnO and TiO_2 literature specifically, plant-mediated and other biologically assisted routes are repeatedly documented as enabling nanoparticle formation under milder conditions and producing functional nanostructures applicable to photocatalysis, antimicrobial systems, and environmental applications [17].

However, the same reviews emphasize a recurring technical limitation: variability and reproducibility. Reaction conditions (pH, temperature, precursor concentration, extract composition) strongly influence particle size distribution and morphology, which then affects performance and risk-relevant behavior such as dissolution and surface reactivity [17]. This becomes critical when nanoparticles are intended for engineered systems (e.g., coatings, cementitious matrices, membranes) where uniformity and predictable behavior are required.

Preliminary synthesis inference

The field shows a consistent trade-off pattern: green routes improve process sustainability but controlling particle uniformity at scale remains a key constraint that must be treated as both a performance and risk issue (because variability changes hazard/exposure behavior) [17], [13], [14].

B. Risk profiles: release, exposure, and lifecycle risk points

1) Lifecycle release from nano-enabled building materials

A major theme in construction-adjacent nanotechnology is that risk does not end at synthesis. Release can occur during mechanical processing (e.g., sanding/cutting), weathering/UV aging, thermal stress, and end-of-life treatment**.** A lifecycle-oriented study of nano-enabled building materials explicitly examined degradation scenarios (mechanical, thermal, environmental aging) and characterized released particulate matter, reinforcing that realistic use-phase and end-of-life conditions are essential for credible risk assessment [18].

Complementing that lifecycle view, earlier emission work on photocatalytic nanocoatings documented weathering-dependent nanoparticle emission patterns, supporting the argument that exposure pathways may evolve rather than remain constant [19].

Preliminary risk inference

Construction-relevant nano-systems require exposure assessment anchored in use-phase and disturbance scenarios, not only "as-produced" material characterization [18], [19].

2) Occupational exposure and risk management emphasis

The occupational health literature consistently highlights measurement and control challenges for nanomaterial exposure, and systematic synthesis of workplace exposure measurement techniques underscores variability in methods and the need for robust, context-specific assessment approaches

[20]. Recent SbD tool development also reflects this, integrating design-stage decisions with workplace exposure reduction strategies in a structured way [21].

Preliminary risk inference

SbD is increasingly operationalized as a practical exposure-reduction workflow, not just a conceptual aspiration, but it still depends on high-quality exposure characterization and scenario realism [21], [20].

C. Governance trends: convergence around SSbD, but uneven operational adoption

1) EU SSbD framework as a central organizing trend

A clear governance trend since 2022 is the EU's push toward a standardized SSbD assessment framework for chemicals and materials, explicitly intended to be tested and iteratively improved with stakeholder feedback [13]. The JRC technical foundation for SSbD consolidates safety and sustainability dimensions, methods, indicators, and tools, and anchors SSbD in lifecycle thinking and circular economy compatibility [14].

Together, these sources reflect a shift from fragmented "safe by design" discussions to a structured, testable assessment logic that aims to produce usable criteria and decision thresholds over time [13], [14].

2) Design-phase tools and tiered decision logic

In parallel, the research community is building design-phase screening tools aligned with SSbD thinking. AdMaCat is one example of a first-tier screening tool intended for early design decision support, producing recommendations across lifecycle stages (manufacturing, use, end-of-life) and enabling structured comparison during innovation [15].

Preliminary governance inference

SSbD is moving from policy aspiration to practical tooling, but widespread adoption depends on usability, data availability, and the ability to integrate with existing engineering decision processes [13]–[15].

3) Standards landscape and risk communication under uncertainty

ISO/TR 13121 explicitly frames nanomaterial risk evaluation as a process that must operate under uncertainty, emphasizing information needs, decision-making, updating assumptions, and risk communication with stakeholders [16]. This aligns strongly with the educational goal of "risk-informed innovation," because it treats uncertainty management and communication as core competencies rather than peripheral concerns [16], [13].

D. Consolidated preliminary results themes

Based on the reviewed governance, exposure, and synthesis evidence, the current literature supports four defensible preliminary findings:

1. **Green synthesis is advancing rapidly**, with strong evidence that biologically assisted routes can produce functional ZnO/TiO_2 nanostructures while aligning with green chemistry principles, though reproducibility and control remain persistent issues [17].
2. **Risk in nano-enabled construction/environmental systems is lifecycle-driven**, with credible studies demonstrating release and exposure potential under realistic degradation and disturbance scenarios [18], [19].
3. **SSbD is becoming the dominant policy anchor in Europe**, supported by formal recommendations and technical-method foundations that emphasize lifecycle, indicators, and iterative framework testing [13], [14].
4. **Operational SbD is increasingly tool-supported**, especially for workplace exposure reduction, but remains constrained by exposure measurement variability and scenario dependence [21], [20].

V. Discussion: Gap Analysis and Implications for Environmental Engineering

A. Interpretation of synthesis and risk evidence

The literature reviewed shows a clear shift toward green synthesis as a more sustainable way to make nanoparticles than traditional methods. In environmental engineering and construction-related research, biologically mediated synthesis pathways consistently diminish solvent toxicity, reaction intensity, and energy requirements, while preserving efficacy in photocatalytic, antimicrobial, and remediation applications [22], [23]. These findings substantiate the assertion that synthesis route selection is not solely a materials decision, but a primary risk factor affecting subsequent exposure, release, and lifecycle consequences.

Nonetheless, the same body of research indicates that green synthesis alone does not ensure safety. Nanoparticles' size, surface chemistry, and agglomeration behavior can all change, which makes it hard to predict hazards and exposures, especially when nanoparticles are mixed into composite systems like cementitious matrices or surface coatings [18], [24]. From a safer-by-design point of view, this makes it even more important to think of process control and reproducibility as safety-relevant design parameters, not just performance metrics.

B. Persistent gaps in lifecycle risk characterization

Despite increased attention to lifecycle thinking, the review highlights a persistent imbalance between synthesis-focused research and use-phase or end-of-life risk assessment. While multiple studies have characterized release during weathering, mechanical abrasion, or thermal stress [18], [19], these investigations remain the exception rather than the norm. Most green synthesis studies stop at material characterization and short-term functionality testing, leaving exposure pathways under realistic engineering conditions insufficiently explored [22], [23].

This gap has direct implications for environmental engineering practice. Nano-enabled materials deployed in infrastructure or housing are subject to decades of environmental stressors, yet longitudinal data linking synthesis method to long-term release or transformation remain scarce.

The absence of standardized protocols for such assessments complicates regulatory alignment and undermines confidence in sustainability claims [14], [16].

C. Governance convergence and operational tension

At the governance level, the emergence of the European SSbD framework represents a significant step toward harmonizing safety and sustainability considerations across the materials lifecycle [13]. The framework's emphasis on early-stage screening, iterative assessment, and integration of environmental and health indicators aligns well with the design-centric ethos of environmental engineering.

Nevertheless, the literature also reflects operational tension between policy ambition and implementation capacity. Design-phase tools such as AdMaCat and tiered SSbD assessment models provide structured pathways for decision-making [15], [25], yet their uptake depends heavily on data availability, practitioner training, and compatibility with existing engineering workflows. Without formal integration into education and professional standards, these tools risk remaining peripheral rather than transformative.

D. Implications for engineering education

Taken together, these findings suggest that environmental engineering education must evolve beyond descriptive coverage of nanotechnology or sustainability principles. The evidence supports a need for curricula that explicitly connect:

- synthesis decisions to lifecycle risk outcomes,
- material performance to exposure and governance considerations, and
- technical innovation to uncertainty management and ethical responsibility.

The absence of such integration represents a structural gap between research advances and workforce preparedness, particularly in domains where engineers are expected to make design decisions under regulatory and societal scrutiny [9], [11], [16].

VI. Educational Framework for Risk-Informed Innovation

A. Rationale for a risk-informed educational framework

For an audience of engineering students, the most important question is not just whether SbD principles are important in theory, but how they can be realistically integrated into existing curricula without detracting from the core technical content. The proposed framework is modular instead of prescriptive. This means that it is meant to be used in regular engineering courses to help students make decisions based on the whole life cycle and risk, rather than needing new programs to do so.

The reviewed evidence suggests that while safer-by-design and SSbD frameworks are gaining traction in research and policy, their application in engineering education remains limited. Studies on sustainability education consistently show that isolated modules or elective courses are insufficient to produce durable competencies in lifecycle thinking or risk-aware design [9], [26]. Instead, effective learning outcomes are associated with scaffolded, program-level integration that combines technical content with applied decision-making and assessment.

In the context of green-synthesized nanoparticles, this necessitates an educational framework that explicitly links material synthesis, environmental impact, occupational health, and governance. ISO 14001-aligned environmental management principles provide a suitable backbone for this integration, as they emphasize continual improvement, risk identification, and documentation across organizational processes [27].

B. Framework structure and learning progression

The proposed framework is organized into three progressive instructional phases, designed to align with typical environmental engineering curricula while remaining adaptable to institutional constraints.

Phase 1: Foundations of green nanomaterials and environmental risk.

At the introductory level, students develop conceptual understanding of nanoparticle properties, green synthesis routes, and basic hazard mechanisms. Instruction emphasizes comparison between conventional and green synthesis pathways, supported by case studies drawn from peer-reviewed literature [22], [23]. Introductory lifecycle assessment concepts are introduced to frame synthesis decisions within broader environmental systems [9].

Phase 2: Application of safer-by-design and lifecycle tools.

At the intermediate level, students apply SbD and SSbD concepts to design-oriented problems. Project-based learning activities require students to evaluate nano-enabled environmental or construction materials using tiered assessment logic and design-phase screening tools reported in the literature [15], [25]. ISO 14001 principles are operationalized through simulated environmental management scenarios, reinforcing the link between technical design and governance [27].

Phase 3: Integration, governance, and professional judgment.

At the advanced or capstone level, students synthesize technical, environmental, and ethical dimensions through open-ended projects. Emphasis is placed on uncertainty management, stakeholder communication, and policy-aware decision-making, consistent with ISO/TR 13121 guidance on nanomaterial risk evaluation under uncertainty [16]. Students are assessed on their ability to justify design choices using evidence, acknowledge limitations, and propose mitigation strategies.

C. Assessment and validation strategy

Consistent with established engineering education research, the framework, as shown in Figure 2, is intended to be validated through a mixed-method approach. Delphi-based expert consensus methods are effective for validating curriculum structure and learning objectives in engineering contexts [28], [29]. These methods can be combined with pre- and post-instruction assessments measuring gains in sustainability literacy, lifecycle reasoning, and risk awareness [9], [26].

Longitudinal tracking of graduates, while resource-intensive, is recommended to evaluate whether competencies translate into professional practice, addressing a known limitation in sustainability education research [11].

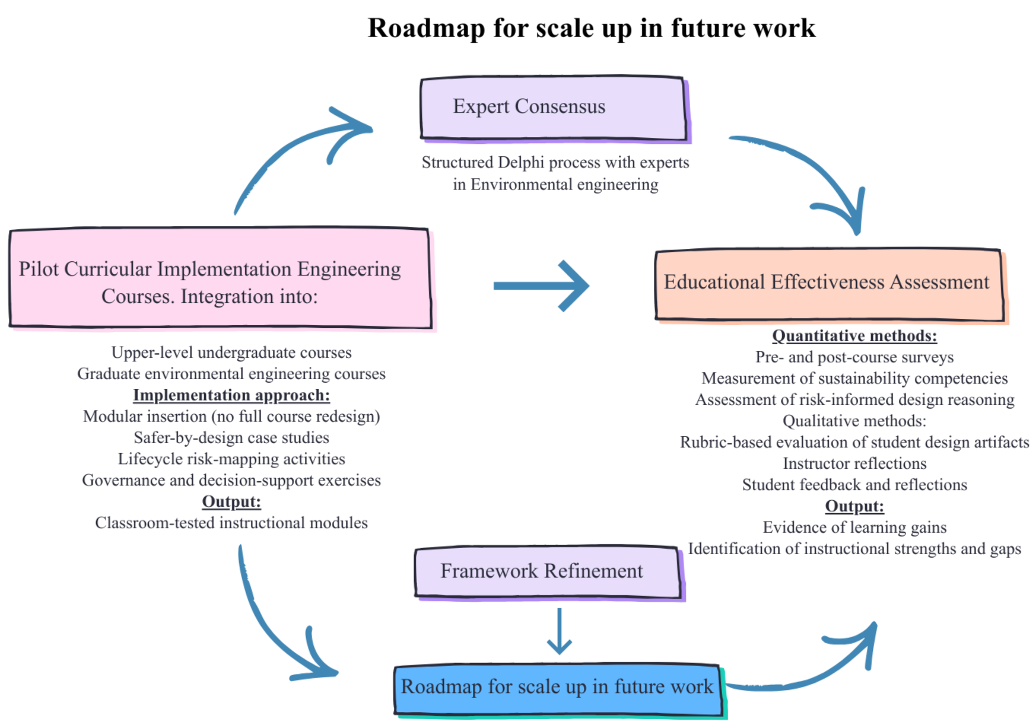

Figure 2: Validation Plan for the Proposed SSbD Pedagogical Framework

D. Anticipated benefits and implementation considerations

By embedding safer-by-design and green synthesis concepts across multiple curricular stages, the proposed framework aligns educational outcomes with evolving governance expectations and industry needs. It prepares environmental engineers to engage in nanotechnology innovation with an explicit understanding of risk, uncertainty, and responsibility, rather than treating safety as an afterthought.

Implementation challenges include faculty training, access to lifecycle assessment tools, and curricular crowding. However, the modular structure of the framework allows institutions to adapt depth and scope without compromising conceptual integrity, consistent with best practices reported in sustainability-oriented engineering education studies [26], [27].

VII. Sample of the Course Integration Pathways

The proposed framework is intended for integration into existing courses commonly found across engineering curricula. Rather than creating new required courses, SbD and LCA components can be embedded within Table 1:

Table 1: Proposed Integration of Safer-by-Design (SbD) and Life-Cycle Assessment (LCA) Modules Across the Engineering Curriculum

Time Frame	
Year 1–2 (Foundational Exposure)	• Introduction to Engineering (basic lifecycle thinking) • Materials Science (material selection and environmental trade-offs) • Engineering Ethics (responsibility in technology development)
Year 2–3 (Applied Technical Context)	• Manufacturing Processes (nano-enabled production implications) • Transport Phenomena (particle behavior and exposure pathways) • Sustainable Engineering or Environmental Systems
Year 3–4 (Design Integration)	• Engineering Design courses • Capstone Design projects • Risk Assessment or Process Design electives

Conclusions and Future Work

A. Conclusions

This systematic review synthesizes contemporary, Scopus-indexed research on green-synthesized nanoparticles through the combined lenses of environmental engineering practice, safer-by-design innovation, and engineering education. Across synthesis, risk, and governance domains, the literature consistently demonstrates that green synthesis pathways represent a substantive advancement toward environmentally responsible nanomaterial production, primarily by reducing hazardous reagents, lowering energy demand, and enabling bio-based process chemistry [22], [23], [30].

However, the review also establishes that green synthesis alone is insufficient to guarantee safety or sustainability. Variability in particle morphology, surface chemistry, and aggregation behavior introduces uncertainty into hazard characterization and exposure assessment, particularly when nanoparticles are deployed in complex environmental or construction systems [18], [24]. These uncertainties underscore the importance of integrating safer-by-design and lifecycle-based decision frameworks early in material development, rather than relying on post hoc risk mitigation.

At the governance level, the emergence of the European safe-and-sustainable-by-design (SSbD) framework marks a pivotal shift toward harmonized, lifecycle-oriented evaluation of advanced materials [13], [14]. Design-phase tools and tiered assessment approaches increasingly operationalize these principles, offering structured pathways for early screening and iterative improvement [15], [25]. Nonetheless, their impact remains constrained by data gaps, limited standardization, and uneven uptake across engineering domains.

From an educational perspective, the review highlights a persistent disconnect between advances in nanomaterial safety research and formal engineering curricula. While sustainability and environmental management concepts are increasingly emphasized, explicit treatment of nanomaterial risk, uncertainty, and governance remains fragmented [9], [26]. The proposed educational framework addresses this gap by embedding green synthesis, safer-by-design, lifecycle assessment, and ISO 14001-aligned governance across progressive stages of environmental engineering education.

B. Contributions to environmental engineering education and practice

This work makes three primary contributions:

1. **Evidence synthesis**: It consolidates recent, high-quality evidence linking green synthesis routes to environmental and occupational risk considerations across the nanomaterial lifecycle, with direct relevance to environmental engineering applications.
2. **Risk-informed interpretation**: It reframes synthesis variability, reproducibility, and scale-up challenges as safety-relevant design parameters rather than purely technical limitations, aligning with safer-by-design principles.
3. **Educational advancement**: It proposes an evidence-grounded, modular educational framework that translates SSbD governance logic into teachable competencies, preparing future engineers to navigate innovation under uncertainty and regulatory scrutiny.

C. Limitations

Several limitations must be acknowledged. First, while the review adheres to PRISMA-aligned methodology, heterogeneity in study design, reporting metrics, and application contexts precluded quantitative meta-analysis. Second, much of the available risk evidence remains short-term or laboratory-based, limiting conclusions about long-term environmental and occupational outcomes. Finally, governance frameworks such as SSbD are still in active development, and their criteria and indicators may evolve as implementation feedback accumulates [13], [14].

D. Future research directions

The reviewed literature points to clear priorities for future work:

- Standardized comparative studies directly evaluating green versus conventional synthesis routes using harmonized performance, toxicity, and lifecycle metrics.

- Longitudinal exposure and transformation studies examining nano-enabled materials under realistic environmental and use-phase conditions.
- Operationalization of SSbD through validated, domain-specific indicators that integrate seamlessly with engineering design workflows.
- Educational validation research**,** including multi-institutional implementation of the proposed framework and longitudinal tracking of graduate competencies in professional practice.

It is also paramount to note that this study is the first step in a larger research program that aims to make safer-by-design (SbD) and lifecycle-informed innovation a part of engineering education. The next step in the work will be to use a Delphi process to gather structured expert feedback on the learning goals, the order in which lessons are taught, and how students are tested.

After expert refinement, the framework will be tested in upper-level undergraduate engineering courses and integrated into design, materials, and manufacturing courses in a modular way. The empirical evaluation will consist of pre- and post-course assessments of sustainability competencies, an analysis of student design artifacts utilizing rubric-based criteria, and qualitative feedback from both instructors and students.

In the next phases, different institutions will work together to test how well the program works for environmental, chemical, materials, and mechanical engineering programs. This wider use will make it possible to compare how different disciplines adopt new ideas, how easy they are to teach, and how hard they are to integrate over the long term.

The ultimate objective of ongoing research is to evolve from the development of conceptual frameworks to evidence-based curricular reform that integrates risk-informed innovative practices across engineering disciplines.

As nanotechnology continues to expand within environmental engineering, the ability to innovate responsibly will depend on engineers who are technically proficient, risk-aware, and governance-literate. Embedding safer-by-design thinking and green synthesis principles into engineering education is, therefore, not optional, but essential for aligning technological progress with public health and environmental stewardship.

References

[1] C. Mullins-Jaime and T. D. Smith, “Nanotechnology in residential building materials for better fire protection and life safety outcomes,” *Fire*, vol. 5, no. 6, p. 174, 2022.

[2] A. Brunelli, A. Serrano Lotina, M. A. Bañares, V. Alcolea Rodríguez, M. Blosi, A. Costa, S. Ortelli, W. Peijnenburg, C. Fitó-López, E. González Fernández, J. Hermosilla, L. G. Soeteman-Hernández, I. Garmendia Aguirre, H. Rauscher, F. A. Murphy, V. Stone, J. Balbuena, J. M. Lloris Cormano, L. Pizzol, D. Hristozov, A. Marcomini, and E. Badetti, “Safe-by-design assessment of SiO_2@ZnO multi-component nanomaterial used in construction,” *Environmental Science: Nano*, vol. 12, no. 1, Jan. 2024, doi: 10.1039/D4EN00352G.

[3] A. Kostapanou, K. R. Chatzipanagiotou, and S. Damilos, “Safe-and-sustainable-by-design framework: (Re-)designing the advanced materials lifecycle,” *Advanced Materials Technologies*, vol. 9, no. 5, 2024.

[4] R. Packroff and R. Marx, “Safe and sustainable by design—An interdisciplinary challenge for future-proof chemistry,” *ChemPlusChem*, vol. 87, no. 1, 2022.

[5] S. Dekkers, V. Adam, V. Di Battista, A. Haase, J. Prinz, G. Nagel, W. Fransman, M. Persson, B. Suarez-Merino, W. Wohlleben, O. Schmid, and E. P. van Someren, “Safe-and-sustainable-by-design approach and decision support system for advanced materials,” *Advanced Sustainable Systems*, vol. 9, no. 10, Sep. 2025, doi: 10.1002/advs.202500208.

[6] H. Ben Jeddi, H. Goede, R. Franken, E. van Someren, N. Shandilya, R. Vermoolen, J. Steck, S. Artous, J. S. Hermosilla, and W. Fransman, “Development of a nano-specific safe-by-design module to identify risk management strategies,” *Annals of Work Exposures and Health*, vol. 69, no. 3, pp. 310–322, Mar. 2025, doi: 10.1093/annweh/wxae088.

[7] B. Harlow, “Bionanomaterials to avoid the environmental hazards of conventional nanoparticles,” in *Biopolymeric Nanomaterials: Fundamentals and Applications*. Elsevier, 2023.

[8] A. R. Medina, S. F. Hansen, F. J. Rodríguez Macías, and A. Baun "A design-phase environmental safe-and-sustainable-by-design categorization tool for nano-enabled advanced materials (AdMaCat)," *Environmental Science: Nano*, vol. 11, no. 4, pp. 1456-1472, 2024.

[9] J. Deng, L. Du, J. Xia, Y. Li, and X. Cai, "Eco-design learning framework on integrating life cycle assessment into engineering courses for sustainability competency enhancement," *IEEE Access,* vol. 9, pp. 156789–156801, 2021.

[10] L. Wang, J. Yuan, J. He, H. Li, and Z. Huang, "Developing green design competencies in engineering undergraduates," *Engineering Reports*, vol. 7, no. 8, Art. no. e70343, Aug. 2025, doi: 10.1002/eng2.70343.

[11] M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. W. Loder, E. Mayo-Wilson, S. McDonald, L. A. McGuinness, L. A. Stewart, J. Thomas, A. C. Tricco, V. A. Welch, P. Whiting, and D. Moher, "The PRISMA 2020 statement: An updated guideline for reporting systematic reviews," *BMJ*, vol. 372, p. n71, Mar. 2021, doi: 10.1136/bmj.n71.

[12] PRISMA Statement, "PRISMA 2020 statement and reporting resources," 2020–2021.

[13] European Commission, "Commission recommendation of 8.12.2022 establishing a European assessment framework for 'safe and sustainable by design' chemicals and materials," Brussels, C(2022) 8854, 2022.

[14] C. Patinha Caldeira, R. Farcal, C. Moretti, L. Mancini, H. Rauscher, K. Rasmussen, J. Riego Sintes, and S. Sala, *Safe and Sustainable by Design Chemicals and Materials: Review of Safety and Sustainability Dimensions, Aspects, Methods, Indicators, and Tools*, EUR 30991 EN, Publications Office of the European Union, Luxembourg, 2022, doi: 10.2760/879069.

[15] K. R. Chatzipanagiotou, F. Petrakli, J. Steck, C. Philippot, S. Artous, and E. P. Koumoulos, "Towards safe and sustainable by design nanomaterials: Risk and sustainability assessment on two

nanomaterial case studies at early stages of development," *Sustainable Futures*, vol. 9, Art. no. 100511, Mar. 2025

[16] ISO, "ISO/TR 13121: Nanotechnologies — Nanomaterial risk evaluation," International Organization for Standardization, 2011 (actively maintained listing).

[17] R. A. Gonçalves, R. P. Toledo, N. Joshi, and O. M. Berengue, "Green synthesis and applications of ZnO and TiO_2 nanostructures," *Molecules*, vol. 26, no. 8, Art. no. 2236, Apr. 2021, doi: 10.3390/molecules26082236.

[18] D. Singh, A. Marrocco, W. Wohlleben, H. R. Park, A. R. Diwadkar, B. E. Himes, Q. Lu, D. C. Christiani, and P. Demokritou, "Release of particulate matter from nano-enabled building materials (NEBMs) across their lifecycle: Potential occupational health and safety implications," *Journal of Hazardous Materials*, vol. 422, Art. no. 126771, Jan. 2022, doi: 10.1016/j.jhazmat.2021.126771.

[19] N. Shandilya, O. Le Bihan, C. Bressot, and M. Morgeneyer, "Emission of titanium dioxide nanoparticles from building materials to the environment by wear and weather," *Environmental Science & Technology*, vol. 49, no. 4, pp. 2163–2170, Feb. 2015, doi: 10.1021/es504710p.

[20] F. Boccuni, D. Gagliardi, R. Ferrante, B. M. Rondinone, and S. Iavicoli, "Measurement techniques of exposure to nanomaterials in the workplace for low- and medium-income countries: A systematic review," *International Journal of Hygiene and Environmental Health*, vol. 220, no. 7, pp. 1089–1097, Oct. 2017, doi: 10.1016/j.ijheh.2017.06.003.

[21] H. Ben Jeddi, H. Goede, R. Franken, E. van Someren, N. Shandilya, R. Vermoolen, J. Steck, S. Artous, J. S. Hermosilla, and W. Fransman, "Development of a nano-specific safe-by-design module to identify risk management strategies," *Annals of Work Exposures and Health*, vol. 69, no. 3, pp. 310–322, Mar. 2025, doi: 10.1093/annweh/wxae088.

[22] H. Y. Devadula Sai Rama, A. N. Anitha Yellumala, and S. G. Abraham Manuel, "Green synthesis of ZnO nanoparticles using *Delonix elata* and *Gynura cusimbua* leaf extracts and

evaluating their in-vitro antibacterial properties," *Journal of Advanced Scientific Research*, vol. 15, no. 1, pp. 1–5, 2024, doi: 10.55218/JASR.2024.1501.

[23] A. Barhoum, J. Jeevanandam, and M. K. Danquah, *Fundamentals of Bionanomaterials*, 1st ed. Amsterdam, The Netherlands: Elsevier, 2021, ISBN: 978-0-12-824147-9.

[24] H. D. Romero-Cantú, I. Furxhi, C. T. P. Coelho, *et al*., "Current knowledge for implementing safe and sustainable by design across the life cycle of nanosilver textiles," *Discover Sustainability*, vol. 6, Art. no. 1353, Dec. 2025, doi: 10.1007/s43621-025-02092-x.

[25] A. Livieri, S. Devecchi, L. Pizzol, A. Zabeo, S. Stoycheva, M. J. López-Tendero, A. Brunelli, E. Badetti, E. Semenzin, and D. Hristozov, "Assessing safety and sustainability performance of advanced nanomaterials: A tiered approach along the innovation process," *NanoImpact*, vol. 39, Art. no. 100573, 2025, doi: 10.1016/j.impact.2025.100573.

[26] J. Deng, L. Du, J. Xia, Y. Li, and X. Cai, "Eco-design learning framework on integrating life cycle assessment into engineering courses for sustainability competency enhancement," *IEEE Access*, vol. 9, pp. 160596–160606, 2021, doi: 10.1109/ACCESS.2021.3132335.

[27] ISO, *ISO 14001:2015 Environmental Management Systems — Requirements with Guidance for Use*, International Organization for Standardization, Geneva, Switzerland, 2015.

[28] R. A. Khan, A. Spruijt, U. Mahboob, M. A. Eraky, and J. J. G. van Merriënboer, "Curriculum viability indicators: A Delphi study to determine standards and inhibitors of a curriculum," *Evaluation & the Health Professions*, vol. 44, no. 2, pp. 210–222, Jun. 2021, doi: 10.1177/0163278720934164.

[29] T. Zhao, J. Zhu, Z. Jian, X. Zhou, S. Yang, and P. Zhang, "Developing an effective system for engineering management education: A teaching practice and evaluation perspective," *Education Sciences*, vol. 14, no. 12, Art. no. 1412, Dec. 2024, doi: 10.3390/educsci14121412.

[30] R. Packroff and R. Marx, "Safe and sustainable by design—An interdisciplinary challenge for future-proof chemistry," *ChemPlusChem*, vol. 87, no. 3, Art. no. e202100534, Feb. 2022, doi: 10.1002/cplu.202100534.

[31] A. Kostapanou, K.-R. Chatzipanagiotou, S. Damilos, F. Petrakli, and E. P. Koumoulos, "Safe-and-sustainable-by-design framework: (Re-)designing the advanced materials lifecycle," *Sustainability*, vol. 16, no. 23, Art. no. 10439, Nov. 2024, doi: 10.3390/su162310439.

[32] S. Mukwarami and H. M. van der Poll, "A theoretical approach to address environmental management accounting implementation barriers in small and medium enterprises in developing countries," *Discover Sustainability*, vol. 5, Art. no. 385, Nov. 2024, doi: 10.1007/s43621-024-00598-4.