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Understanding the Benefits and Risks of Sustainable Nanomaterials in a Research Environment

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Abstract: Nanomaterials hold immense potential for numerous applications in energy, healthcare, and environmental sectors, which contribute to achieving sustainable development goals (SDGs) such as improved healthcare and cleaner environments. Their utilization spans from improving energy efficiency to enhancing medical diagnostics and mitigating environmental pollution, thus presenting a multifaceted approach to achieving sustainability goals. To ensure the sustainable and safe utilization of nanomaterials, a thorough evaluation of potential hazards and risks is required throughout their lifecycle – from resource extraction and production to use and disposal. In this review, we focus on understanding and addressing potential environmental and health risks associated with nanomaterial utilization. We advocate for a balanced approach to nanomaterial development and utilization, with early hazard identification, safe-by-design principles, and life cycle assessments, while emphasizing safe handling and disposal practices, collaborations, and continuous improvement. Our goal is to ensure responsible nanomaterial development for nanotechnology, fostering innovation alongside environmental and community well-being, through a holistic approach integrating science, ethics, and proactive risk assessment.

Keywords: Circular economy · Life cycle assessment · Nanomaterials · Risk assessment · Sustainable nanotechnology

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1. Introduction

As defined by the International Standard Organization (ISO/TS 27687), nanomaterials are materials engineered at the nanoscale, ranging from 1–100 nanometers, with at least one external dimension or internal structure falling within this size range.[1] These materials exhibit unique physical and chemical properties at the nanoscale, characterized by an increased surface area to volume ratio, leading to enhanced reactivity and size-dependent properties that can be tailored for specific applications.[2,3] This intrinsic uniqueness presents exciting opportunities across various domains, contributing to *advancements in healthcare* (**SDG 3**)[4] and *environmental protection* (**SDG 12**).[5,6] For instance, in the energy sector, nanomaterials enhance energy efficiency and stor-

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age capacity in solar cells and batteries, facilitating the transition towards renewable energy sources and reducing reliance on fossil fuels.[7,8] In healthcare, using nanomaterials for targeted drug delivery offers the advantage of minimizing side effects and enhancing treatment efficacy, consequently reducing resource consumption in healthcare.[9,10] Furthermore, nanomaterials are relevant in material manufacturing by developing lighter and stronger materials, potentially leading to more efficient resource utilization.[11] Additionally, nanomaterials could play a significant role in water purification technologies and antimicrobial food packaging in environmental applications, thereby contributing to a cleaner and healthier environment.[12–14] The transformative impact of nanomaterials extends across industries, ushering in innovative and sustainable solutions.[15,16]

Sustainable nanotechnology actively promotes the circular economy theory, which calls for designing, producing, and using nanomaterials to maximize resource efficiency.[16] This advocates for a closed-loop system where resources are continuously cycled and reused throughout the life cycle of nanomaterials, focusing on minimizing waste generation and maximizing resource recovery. To achieve this, several key strategies can be implemented, such as:

a) prioritizing the development of nanomaterials with renewable feedstocks and recyclable or biodegradable components;[17]
b) promoting closed-loop production processes that minimize waste generation;[18]
c) encouraging the use of nanomaterials in durable, long-lasting products to extend their lifespan;[19]
d) fostering responsible disposal and recycling of nanomaterials and products containing nanomaterials.[20]

Thus, the integration of sustainable principles not only enhances the functionality of nanomaterials but also ensures their long-term viability for societal benefit.[21] The significant production and use of sustainable nanomaterials and nanomaterial-enabled products that maximize functional performance also face the challenges of minimizing adverse environmental or human health impacts.[22,23]

This review explores the intricate balance between nanomaterials innovation and precaution. To ensure sustainable and safe nanomaterial utilization, it is imperative to evaluate the potential hazards and risks throughout their entire lifecycle, from resource extraction to production, use, and disposal. As nanotechnology progresses from fundamental research to practical laboratory applications, a tiered approach is advocated, encompassing thorough life cycle assessments, safe-by-design principles, and early hazard and risk identification;[16] these aspects will be covered in section 2, including some examples of sustainable nanomaterial use in the healthcare section. The focus in section 3 is on the safe handling and disposal in a research environment working with nanomaterials designed for various applications. Thorough protocols are indispensable, encompassing hazard and risk identification, engineering controls, and stringent handling guidelines.[20]

2. Sustainable Development of Nanomaterials with Low Risks in Healthcare Applications

This section highlights the potential of low-risk nanomaterials to revolutionize healthcare and contribute to advancements aligned with the SDGs. A meticulous selection process, emphasizing rigorous risk assessment, adherence to 'safe-by-design' principles, and strict regulatory compliance, ensures the safety and sustainability of these materials throughout their lifecycle. Promising examples like liposomes and gold nanoparticles play pivotal roles in drug delivery, imaging, diagnostics, and therapy, contributing to enhanced treatment outcomes, reduced resource consumption, and minimized environmental impact, aligning with broader sustainability objectives in healthcare, particularly **SDGs 3** (*Good Health and Well-being*) and **12** (*Responsible Consumption and Production*).[24–27] A comprehensive approach that ensures safety throughout the lifecycle of nanomaterials, from development to production and use, is important. This approach is particularly relevant for applications like targeted drug delivery systems, where nanomaterials can significantly improve treatment efficacy while minimizing side effects.[28] Nanomaterial-based drug delivery systems minimize the overall dosage required for effective treatment by precisely delivering therapeutic agents to specific sites within the body. This reduction improves patient outcomes and reduces pharmaceutical waste and environmental impacts associated with excess medication production and disposal, aligning with sustainability objectives **SDG 12**.[29] Moreover, nanomaterials are instrumental in advancing disease diagnostics, offering heightened sensitivity and accuracy in detection.[30,31] Nanomaterial-based diagnostics enable early disease detection, which allows for timely interventions and promotes sustainable healthcare practices by reducing the need for resource-intensive treatments. Furthermore, these nanomaterials play a significant role in enhancing the performance and biocompatibility of biomedical implants, such as prosthetic devices and tissue scaffolds.[32] By incorporating nanomaterials into these implants, researchers can improve mechanical properties and longevity, thereby reducing the frequency of replacements and minimizing medical waste generation.[33] This enhances patient well-being by improving device functionality and durability and contributes to sustainable healthcare by optimizing resource utilization and minimizing the environmental footprint of medical interventions.[34]

2.1 *Precautionary Approaches*

It is important to acknowledge and address the associated human hazards and safety concerns for sustainable nanomaterials in healthcare during the whole life-cycle, and the following sections cover some concepts that have been developed to address these concerns. These approaches are not specific to healthcare only and can be used for different types of nanomaterials and application fields.

Early Risk Assessment and Hazard Identification: Early in the development process of nanomaterials, it is relevant to identify potential hazards and evaluate the associated risks.[35] Researchers and developers can make informed choices concerning the design of nanomaterials, production methods, and handling techniques by seeing potential risks early on. Taking a proactive approach sets the stage for directly integrating risk mitigation techniques into the development process, which protects people and the environment from harm. Early risk assessment also gives researchers enough time to conduct in-depth hazard identification processes, which allows them to look into potential negative impacts on human health. This foresight facilitates informed decision-making and the early adoption of successful mitigation techniques to prevent prospective harm.

Safe-by-design Principles: Another concept has been introduced as safe-by-design principles. Hazards and risks can be considerably decreased by using non-toxic materials or shielding hazardous components, adding biocompatible coatings, and considering the material's life cycle during the design process to reduce exposure.[36] However, the precautionary principle is important in nanotechnology, where complete hazard and risk data is sometimes lacking.[37,38] This principle can be implemented through various strategies, such as (a) designing for biodegradability and elimination from the environment,[39] (b) selecting materials with minimal toxicity and bioaccumulation potential,[40] (c) ensuring proper surface coatings to reduce interactions with biological systems,[41] (d) implementing closed-loop production and waste management systems,[42] and promoting public disclosure of nanomaterial composition and risks.[43].

Life Cycle Assessment: Promoting sustainable practices requires assessing the effects of nanomaterials on the environment and human health throughout their life cycle, from manufacture and use to disposal. This holistic assessment empowers researchers, manufacturers, users, and policymakers to pinpoint potential environmental hotspots and make well-informed decisions that support environmentally sound practices. This thorough evaluation directs the development of ecologically friendly procedures and guides the development of environmentally responsible practices.[44]

Regulatory Frameworks: Establishing robust regulatory frameworks for nanomaterials is crucial to safeguard the environment and public health, ensuring transparency, confidence, and adaptability to scientific advancements. These frameworks must remain flexible and responsive to changes in nanotechnology, continuously incorporating new data for innovation and safety.

Public Engagement: It is essential to promote open dialogue and actively involve the public in debates concerning the responsible and safe development of sustainable nanomaterials. Public engagement extends beyond simply conveying information. It actively seeks to incorporate a variety of perspectives into discussions about this powerful technology. Through open dialogue, concerns and questions from the public can be addressed transparently, fostering trust, and building a shared understanding of the potential benefits and risks of nanotechnology. This collaborative approach empowers the public to actively participate in shaping the future of nanotechnology, ensuring its development aligns with societal values and promotes responsible innovation. The public may actively influence this game-changing technology's direction by fostering confidence and transparency.[45]

By implementing these precautionary approaches throughout the life cycle of nanomaterials in healthcare, we can ensure responsible innovation that safeguards human health and the environment (Fig. 1). This contributes to achieving broader sustainability goals outlined in the SDGs, particularly **SDG 3** and **SDG 12**.

3. Safe Handling and Disposal of Nanomaterials in Research Environments

This section of the review focuses on safety protocols within research environments; the meticulous handling and disposal of nanomaterials directly contributes to SDGs outlined by the United Nations: **SDG 3**: *Good Health and Well-being* and **SDG 12**: *Responsible Consumption and Production*.

a) By minimizing risks associated with nanomaterials in research settings, we can ensure the safety of researchers and minimize the potential for harm to human health, aligning with **SDG 3**.
b) Responsible disposal practices, ensure we minimize the negative impact of nanomaterials throughout their life cycle. This aligns with the principles of sustainable production and consumption as outlined in **SDG 12**.

A comprehensive understanding of the hazards and risks associated with nanomaterial development at the earliest stages is crucial for ensuring the safe handling and disposal of these materials in research environments. This entails conducting thorough analyses of nanomaterial properties, including size, shape, and surface chemistry, to identify potential hazards before their utilization.[46,47] This is followed by performing a risk analysis, including the emission and potential exposure.[48] Well-established databases such as NanoData and the OECD Harmonized Manufactured Nanomaterial Database are reputable resources for obtaining thorough characterization data.[49,50] It also becomes crucial to conduct a comprehensive risk assessment based on the qualities described and possible exposure situations.[51] This evaluation considers the possibility that the nanomaterial will cause

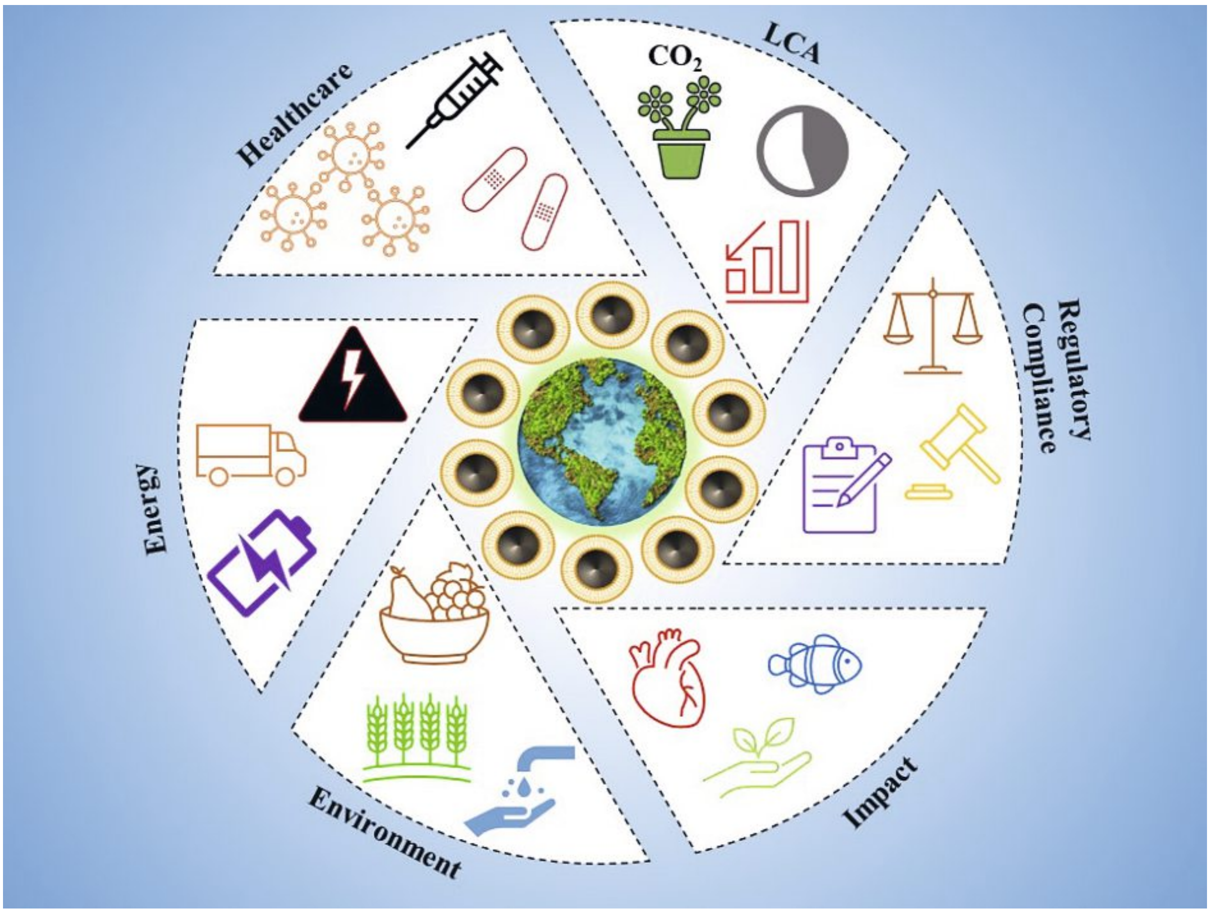

Fig. 1. Schematic representation of nanomaterials applications with considerations of sustainability through Lifecycle assessment (LCA) and Regulatory Compliance.

harm in the first place(hazard) and the possibility that damage will occur in a particular laboratory setting (risk).

Safety management in research laboratories: Recently, a user-friendly method for determining precautionary risk levels for research laboratories was developed as shown in Fig. 2. This safety management system is based on three levels and the precautionary principle. The first step is to determine the hazard band of the nanomaterial using a combination of decision trees and matrices. In the second step, the hazard is linked to the emission and exposure potential. Finally, the technical, organizational, and personal protective measures to allow nanomaterial processes to be established in research environments are outlined.[49,52] In addition, tools like the NIOSH Nanomaterial Exposure Assessment Tool and EU's REACH offer valuable guidance for comprehensive risk assessments.[53,54]

Prioritizing Containment and Minimizing Exposure: After hazard identification, the implementation of engineering controls is crucial. Utilizing closed systems such as glove boxes and fume hoods effectively contains nanomaterials, mitigating the potential for airborne dispersion.[55] Additionally, local exhaust ventilation (LEV) equipped with HEPA filters serves to capture and prevent the escape of nanomaterials, thereby enhancing laboratory safety.[56]

Personal Protective Equipment (PPE): The correct choice and application of PPE is indispensable for ensuring the safety of researchers handling nanomaterials.[57] Selection of gloves should be based on thorough consideration of nanomaterial characteristics and their potential to permeate the skin, drawing on available literature and collaboration with industrial hygiene experts to ensure optimal protection.[58] Respirators meeting N95 or superior filtration standards, specifically certified for nanomaterial use, are required for respiratory safety.[59] Moreover, lab coats and protective eyewear are imperative to shield against direct contact with potentially hazardous nanomaterials.[60]

Safe Handling Procedures: Safe nanomaterial handling relies on meticulous protocols beyond equipment alone. Minimizing direct contact with dry nanomaterials by using scoops or spatulas reduces exposure risks significantly.[61] To minimize potential risks, regular decontamination of work surfaces and equipment with appropriate cleaning solutions is crucial. It is important to avoid techniques that could unintentionally release nanomaterials as aerosols into the environment.[62] Proper disposal of contaminated waste is imperative, as well as preventing disposal down drains or with regular lab waste. Consulting specialized waste disposal companies knowledgeable in nanomaterial handling ensures compliance with regulations, mitigating environmental risks. Incineration with suitable filters or landfilling in designated hazardous waste facilities may be appropriate disposal options depending on the specific nanomaterial and local regulations.[20]

Safe Disposal of Nanomaterials: Improper disposal of nanomaterials can significantly impact wastewater treatment systems and the environment, jeopardizing the long-term sustainability of their use. Safe disposal practices are, therefore, essential.[63] Seeking guidance from specialized waste disposal firms familiar with the unique challenges of handling nanomaterials is crucial for responsible management of these resources.[64] Moreover, strict compliance with regulations is imperative to ensure proper handling and disposal of nanomaterials in accordance with established protocols.[65]

Careful evaluation of the environmental implications associated with nanomaterial disposal is critical in scientific research and industrial practices. This assessment serves as a guide in determining suitable disposal methods, considering factors such as nanomaterial characteristics and regulatory frameworks.[66] Options for disposal may include depositing nanomaterials in designated hazardous waste facilities or subjecting them to controlled incineration with appropriate filtration systems.[67] These decisions aim to minimize adverse effects on ecosystems and human health, aligning with the broader goal of sustainability in nanomaterial utilization.

The safe and responsible disposal of nanomaterials is fundamental to their sustainable application in various fields. Effective nanomaterial waste management requires collaboration with specialized waste management entities and strict adherence to regulatory protocols. Through meticulously evaluating environmental implications and adopting appropriate measures, stakeholders can mitigate potential risks posed by nanomaterials, promoting a more sustainable approach to their utilization, and safeguarding environmental integrity and public health for future generations.

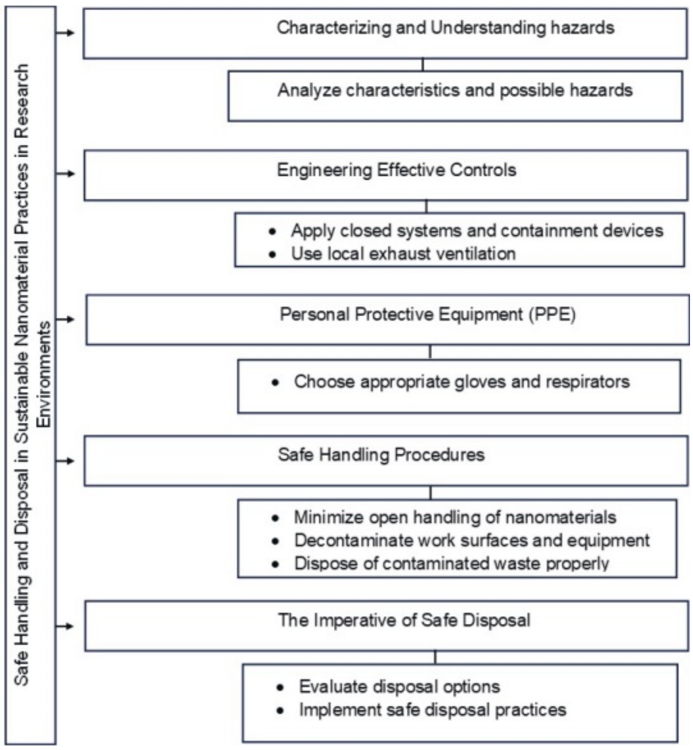

Fig. 2. Overview of Safe Handling and Disposal Practices for Sustainable Nanomaterials in Research Environments.

4. Conclusion

The life cycle assessments, safe-by-design principles, and early hazard recognition are fundamental to minimizing risks throughout a nanomaterial's lifecycle. However, true sustainability demands a broader perspective. To ensure the sustainable development of nanomaterials, specific actions, and proactive safety measures are crucial. Integrating safety throughout all stages, from design to disposal, is a key element of this approach.

With the enormous potential of nanotechnology in numerous applications, we must proceed cautiously to ensure its sustainability. Life cycle evaluations, safe-by-design, and early hazard recognition are important aspects to reducing risks. Clear guidelines, open communication, and global cooperation form the foundation for responsible development that prioritizes environmental and public health protection. Rigorous handling protocols, efficient controls, and integrated safety measures are recommended across the entire nanomaterial lifecycle. Furthermore, open dialogue, continuous improvement, and policies prioritizing both progress and precaution are necessary ethical and social pillars. In the nanotechnology era, redefining 'sustainable safety' is not simply a goal but also a collective responsibility. By integrating scientific knowledge, ethical decision-making, and public engagement, we can harness the promise of nanotechnology to protect the environment and local communities. Together, driven by our shared ideals, let's clear the path for responsible innovation to create a future that can benefit from the great potential of nanotechnology.

4.1 *Specific Actions for Sustainable Safety*

- *Integrating Safety into the Fabric of Sustainability - A Proactive Approach for Long-Term Impact:*

  True sustainability demands a broader perspective beyond reducing direct risks in the lab, in which safety is integrated into the design and use of nanomaterials as a fundamental component. This holistic perspective offers long-term benefits for the environment and human health, directly contributing to two SDGs outlined by the United Nations: **SDG 3** (*Good Health and Wellbeing*) and **SDG 12** (*Responsible Consumption and Production*).

- *Life Cycle Assessment (LCA) - A Holistic View from Cradle to Grave:*

  As previously stated, it becomes evident to carry out a strict LCA over the whole nanomaterial lifecycle.[44] This comprehensive strategy carefully identifies and reduces potential environmental impacts at every stage, from initial development and production to final usage and disposal.[65] Researchers may reduce their environmental impact and contribute to a sustainable future using resources like the OECD Guidance Manual on Developing and Evaluating Environmental Labels for Nanomaterials.[68]

- *The Precautionary Principle - When Uncertainty Demands Caution:*

  The precautionary principle is crucial in managing potential safety hazards and uncertain environmental impacts associated with nanomaterials. This idea requires taking more precautions, enforcing stronger safety regulations, and undertaking in-depth research until new information is obtained. Adopting this concept guarantees responsible development and reduces the likelihood of unanticipated harmful long-term effects.[69]

- *Transparency and Communication - Sharing Knowledge for Collective Advancement:*

  To ensure the safe and sustainable development of nanomaterials, fostering open communication and collaboration among researchers, industry professionals, regulatory agencies, and the public is important. A shared accountability and group advancement culture is fostered by exchanging best practices, research findings, and possible hazards. Moreover, engaging in open dialogue with the public builds trust and understanding, addresses concerns, and ensures broader support for responsible nanotechnology development.[70]

- *Continual Improvement - A Journey of Learning and Adaptation*:

  The field of nanomaterials is dynamic and constantly evolving. Recognizing this, researchers must cultivate a culture of continuous improvement, regularly reviewing and updating safety protocols in light of new research, changing regulations, and emerging technologies. Investing in ongoing training and educational programs for researchers becomes essential, ensuring everyone involved possesses the latest knowledge and skills for safe handling and responsible disposal.[16]

- *Investing in Safe Infrastructure and Technologies:*

  Investing in safer infrastructure and technology is crucial for the shift towards sustainable nanomaterial practices. Investing in creating cutting-edge containment devices, enhanced ventilation systems, and creative disposal techniques reduces environmental emissions and protects public health. Long-term sustainable solutions are also promoted by funding research into intrinsically safer nanomaterials with lower toxicity and environmental effects.[52]

- *Policy and Regulatory Support - Setting the Framework for Responsible Innovation*:

  Well-designed legal and policy frameworks can unlock the full potential of secure and environmentally friendly nanomaterials by fostering innovation and responsible use. Working with regulatory agencies to provide precise norms and standards suited to nanoparticles' unique characteristics is imperative. Additionally, supporting funding for studies into risk management techniques and safety assessment methodologies enables academics to appropriately traverse this developing sector's complexity.[71]

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Author contributions

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