

ADVANCING GREEN TECHNOLOGY THROUGH GLOBAL COLLABORATION IN NANOMATERIAL INNOVATION: A PATH TOWARDS SUSTAINABLE DEVELOPMENT

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Abstract

Nanomaterial innovation has presented new possibilities for creating green technologies that solve multifaceted environmental problems and contribute to sustainable development. Nanomaterials with their property of size and shape dependent characteristics, large surface to volume ratio and multimorph functionality are facilitating advancements in energy storage, water and agriculture, and consumer goods. However, these pioneering materials can only be marketed successfully with the help of multi-national efforts on the part of researchers, industry, and government. The current developments in green nanotechnology and SSbD will be discussed in this paper with theoretical underpinnings from green chemistry and systems theory. The paper focuses primarily on investigating international research networks, quantitative LCA, and regulatory systems. It then proposes a new approach to understanding global research networks, policy strategies, innovation mechanisms, and the outcomes of sustainability endeavours. The issues of the static nature of the current regulatory systems, the necessity of the dynamic risk assessment for smart nanomaterials, and socio-economic impediments to technology transfer are also outlined, along with suggestions for further work. In conclusion, the paper claims that effective cooperation and harmonization of efforts at the global level and based on data can make nanomaterial innovation a major driver of circular, climate-neutral and sustainable development.

Keywords: green technology, nanomaterial innovation, sustainable development, global collaboration, smart nanomaterials, safe-by-design, circular economy, regulatory frameworks

List of Abbreviations/Symbols:

- SSbD: Safe-and-Sustainable-by-Design
- LCA: Life Cycle Assessment
- OECD: Organisation for Economic Co-operation and Development
- REACH: Registration, Evaluation, Authorisation and Restriction of Chemicals
- EU: European Union
- FDA: U.S. Food and Drug Administration

1. Introduction

Environmental sustainability is one of the biggest problems of the present society. As the population of the world grows, and resources are depleted, and pollution increases, our society is faced with the challenge of finding new and improved ways of solving current technological needs

as well as ensuring sustainable development (OECD, 2013). Green technology presents a viable approach in the goal of minimizing environmental footprint while at the same time meeting development objectives pertaining to economic and social development. Among the new technologies, nanomaterial-based innovations have been of interest due to their unique characteristics including high reactivity, high tunability and high functionality. These properties offer potential for revolutionary use across various industries such as energy, water treatments, farming, and innovative consumer goods (Gottardo et al., 2021; Lu & Ozcan, 2015).

However, while the number of publications in the field of nanomaterials has increased rapidly, there are still many unanswered questions—most notably regarding the development of ‘intelligent’ or ‘smart’ nanomaterials. However, this paper identifies several limitations in the current literature: only a limited number of studies has considered the dynamic behaviour of nanomaterials across their life cycle and, even fewer have provided quantitative comparisons using metrics such as LCAs (Subramanian et al., 2010). However, current international collaborations have not been well linked to interdisciplinary research, and the legal and regulatory systems remain undeveloped in many aspects (European Commission, 2011). The literature on sustainable entrepreneurship indicates that robust educational programmes and development of entrepreneurial intention are vital to the growth of sustainable technologies such as green nanotechnology. For example, a study on factors influencing entrepreneurial intention of higher education students within the setting of sustainable tourism reveals that sustainability concept can positively impact the decision making and innovation (Mehraj et al., 2023).

The purpose of this paper is two fold. First, it develops a theoretical framework that links green chemistry and systems thinking to the new paradigm of SSbD for Smarter Nanomaterials. Second, it provides an analytical assessment of the part played by collaboration on the global stage—the research networks, policy frameworks, and industry partnerships in advancing green nanotechnology. In this paper, the author synthesises quantitative data from the literature, case studies and policy analyses to provide a new conceptual framework that builds on current gaps in the literature and points to potential future research directions. The structure of this paper is as follows: Chapter 2 gives an overview of the theoretical framework and the literature review; Chapter 3 focuses on the Case Studies of Global Collaboration; Chapter 4 analyses the International Policy Frameworks and Regulatory Initiatives; Chapter 5 explains the Methodology used in this research; Chapter 6 describes the Conceptual Framework Model and lists Table of Key Studies; Chapter 7 discusses the results of the study and their implications; and Chapter 8 concludes and suggests Directions for Future Research.

2. Theoretical Background

2.1 Theoretical Foundations: Green Chemistry and Systems Theory

Green nanotechnology is based on the concept of green chemistry which was defined systematically by Anastas and Eghbali (2010). Green chemistry is the process of developing a new product or process that will minimize or eliminate the use of hazardous substances. Some of its fundamental rules like atom economy, energy efficiency, and the choice of feedstock from renewable sources can be regarded as a rational approach to designing eco-friendly nanomaterials. In the context of nanomaterial synthesis, these principles can greatly decrease the environmental impact of chemical processes, decreasing waste generation and energy use (Khan, 2020).

Systems theory thereby aids in the analysis of sustainable technologies because it also recognise the fact that every entity is part of a system. Roco (2004) stated that for nanomaterials, an effective

evaluation should consider the environmental, economic, and social life cycle of the materials from extraction, production, application, and disposal. In this context, life cycle assessments (LCAs) can be used to analyze these interactions quantitatively, but many works show that some features of smart nanomaterials may not be well described by current LCA methods (Salieri et al., 2018).

2.2 Literature Review: Advances and Gaps

The current literature review on green nanotechnology has revealed the recent developments in the synthesis, characterization and use of nanomaterials. Lu and Ozcan (2015) provided the information on the green synthesis that can be implemented to decrease energy usage and emissions of the hazardous substances. In the same way, Gottardo et al. (2021) have discussed how the advancement of effective smart nanomaterials that can modify their characteristics in response to stimuli such as temperature, pH and light leads to the creation of new and innovative solutions for water treatment technologies, and controlled release systems (Yoshida & Lahann, 2008; Subramanian et al., 2010).

Nevertheless, the present study identifies several limitations in the literature. Most of them have paid much attention to the efficiency and applicability of the strategies assessed however, little effort has been made on the comparative analysis of the environmental effects. For example, although LCAs are being applied more and more often to evaluate the advantages of green synthesis strategies, there are not many studies that present numerical data on energy efficiency and waste minimization for different methods (Salieri et al., 2018). However, most of the current legal and regulatory definitions of nanomaterials are static and therefore fail to capture the dynamic characteristics of smart nanomaterials (European Commission, 2011; Kuzma & Roberts, 2016).

Other apparent gaps are that risk assessment has not been well coordinated with economic and social impact assessment. Although analytical tools like LICARA NanoSCAN have been devised to measure the environmental and economic effects (Van Harmelen et al., 2016), little research has integrated these quantitative evaluations with systemic policy analyses. Also, there is little consideration of how current risk models need to change to take into account the dynamic behaviour of smart nanomaterials (Plazas Tuttle et al., 2015).

According to the literature, the advances made in developing new nanosynthesis methods and enhancing environmental impacts have been laudable, but there is a lack of innovation in risk assessment models and a lack of a coherent set of rules for regulators globally. This paper extends this work by presenting an integrated SSbD framework that utilizes global collaboration to solve these open questions.

As a result, the analysis of the theoretical background and literature review shows that green nanotechnology is based on the principles of green chemistry and system thinking. Nevertheless, there are some important issues that remain unanswered, including how to assess the lifecycle effects, how to develop dynamic risk models, and how to standardise the international legislation. Therefore, these concerns can be tackled through international cooperation and SSbD approaches to enhance nanomaterial development and SD.

3. Global Collaboration in Nanomaterial Innovation

This paper sought to identify the trends in the global collaboration for the development of nanomaterials especially for green technology. Global problems like climate change, depletion of

natural resources, concern for environment entail systems that involve cooperation among different countries and use of the best resources.

3.1 International Research Networks and Collaborative Platforms

Several international research networks have been developed to promote cooperation of the universities, research organizations, and industries. An example of this is the International Network4Sustainable Nanotechnology that is a consortium of the premier nanoscience institutes from different countries (Mitra et al., 2021). These networks act as platforms for disseminating methodological advances, harmonizing experimental approaches, and tackling the problem of integrating and deploying green nanomaterials. The findings of this study supported the proposition that digital platforms improve collaboration in the global arena through real time networking of resources and knowledge sharing among different stakeholders. Studies of digital commerce networks in India show how, through digital collaboration, geographical and infrastructural constraints can be surmounted to stimulate innovation in growing economies, (Islam et al., 2024).

Other collaborative activities, like NanoHarmony in Europe have been used to build harmonised risk assessment approaches and decision making instruments. Such standardisation enhances the production of comparable data sets which are very important in conducting LCAs and other comparative studies (Soeteman Hernandez et al., 2019). Besides, these international networks contribute to the interdisciplinary collaboration of scholars from chemistry, environmental science, toxicology, and policy analysis. This interdisciplinary approach helps us to develop effective and ecologically friendly smart nanomaterials.

Global partnerships are also useful in the pooling of resources and expertise and, therefore, results in costs efficiencies and fast track technology transfer. Those countries that have well-developed research infrastructure can engage those that are developing their capabilities thus creating a global capacity (Lowry et al., 2019). The sharing of information and knowledge helps to break down the constraints of the partner institutions including lack of funds and inadequate technical capacity to implement and support the best practices.

3.2 Quantitative and Qualitative Case Studies

Real life examples of the advantages of global teamwork. For example, multinational projects associated with smart food packaging have realized measurable decreases in food deterioration, including 20% in some studies, through the creation of packaging systems that can alter their barrier properties depending on levels of gas composition (Brockgreitens & Abbas, 2016; European Commission, 2009). In the same manner, a study of collaborative work on water treatment technologies revealed that green nanomaterial approaches can result in a definite decrease in chemical use and energy intake than conventional ways (Lu & Ozcan, 2015).

Furthermore, economics show that international collaboration holds the potential for cutting costs of research and development by half through splitting and coordinating funding and resources (OECD, 2013). The setting of quantitative targets through LCAs has also enabled researchers to assess the environmental performance of new nanomaterial synthesis methods in contrast to the conventional way and this has provided support to the call for green nanotechnology (Salieri et al., 2018).

Therefore, international cooperation in nanomaterial development enhances scientific advancement and technology diffusion as well as enhances research productivity and the achievement of sustainable goals. International networks help innovation by sharing resources and

setting common methods that produce tangible improvements in environmental outcomes and economic performance.

4. Policy Frameworks and Regulatory Initiatives

For nanomaterial innovation to effectively respond to environmental issues, the latter requires coherent policies, as well as a flexible set of regulations that can be adjusted as needed. These frameworks must therefore seek to meet the technology advancements while at the same time respecting the health of the human being and the environment.

4.1 Regulatory Preparedness

Current conventional approaches, including the European Union's Regulation on Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) and Novel Food Regulation, have largely confined the definition of nanomaterials to a state-based approach based on particle size (European Commission, 2011). Yet, smart nanomaterials behave actively and are responsive to stimuli that are not captured in these definitions (Gottardo et al., 2021). This has led to more and more regulatory authorities demanding new guidelines that reflect more dynamic features and parameters in the risk assessment methodologies, such as reactivity and lifecycle shifts (ECHA, 2019; Kuzma & Roberts, 2016). It is specially important the establishment of dynamic risk models, since the safety features of smart nanomaterials may change over time. New research shows that the existing methods of testing may not capture the dynamic effects or the fact that nanomaterials may be able to phase shift depending on some stimulation (Plazas Tuttle et al., 2015). There is therefore a need for regulatory overhaul that entails the use of time dependent evaluation metrics in order to more accurately quantify and mitigate risk.

4.2 The Safe-and-Sustainable-by-Design (SSbD) Approach

The likely approach to guarantee that the nanomaterial innovations are both safe and sustainable is the SSbD framework. SSbD builds on the principles of green chemistry to the design level by incorporating the principles of environmental, health, and economics in the design process (Anastas & Eghbali, 2010). The literature has indicated that the earliest possible implementation of SSbD practices can greatly minimize the potential negative impacts to the environment and optimise the entire life-cycle of the product under consideration (Soeteman Hernandez et al., 2019). For instance, decision-support tools such as LICARA NanoSCAN provide measures that quantify sustainability, for instance, energy consumption, waste generation and potential economic effects (Van Harmelen et al., 2016).

Moreover, the harmonization of SSbD criteria on the international level is necessary. To this end, some standards organizations like ISO have begun the process of creating guidelines for example ISO/TS 20477 of assessing nanomaterials (ISO/TS 20477, 2017). The studies reveal that European agencies are more explicit about safety and sustainability standards than their counterparts from other continents such as North America and some parts of Asia that focus on market liberalization and innovation. This paper synthesizes these best practices into a harmonized approach that can enable firms to smoothly engage the global market and innovate products that are safe and sustainable.

4.3 Comparative Policy Perspectives

An analysis of the various sets of rules shows that while there has been a lot of improvement, there is still a challenge with the differences across regions. In the European Union, the pre-market assessment and the labelling of nanomaterials are anchored on more defined measures such as the

European Green Deal and the Novel Food Regulation (European Parliament & Council, 2015). However, organizations such as the U.S Food and Drug Administration (FDA) uses the flexible approach which is the case-by-case evaluation that may lead to fast market penetration but bring inconsistency in safety standards (FDA, 2014).

From these differences, it is clear that there is the need for an international platform to discuss and harmonize policies and regulations. For this reason, there is the need to develop new policies and regulatory measures to cope with the emergent characteristics of smart nanomaterials. This paper shows that the concept of combining SSbD principles with adaptive risk assessment approaches is a viable approach towards developing a global framework that can accommodate safe and responsible nanotechnology development.

5. Methodology

To achieve the research objectives of this paper, a mixed-methods approach of systematic literature review and policy analysis is used to examine the effect of global collaboration on green nanomaterial innovation. The study is designed in such a way that the results can be easily replicated and the conclusions made are based on the critical review of literature and policy documents.

5.1 Literature Review Process

The major academic databases such as Scopus, Web of Science were used to conduct the systematic literature review. Key terms including ‘green nanotechnology’, ‘global collaboration’, ‘smart nanomaterials’, ‘life cycle assessment’ and ‘safe by design’ as well as ‘regulatory framework’ were combined to form search strings. To limit the search to up to date research trends, it focused only on peer reviewed articles, policy documents and authoritative industry reports published between 2000 and 2025. It is compulsory that either quantitative data such as LCA metrics and cost benefit analysis or detailed case studies which evaluate the sustainability and regulatory issues with regard to the use of nanomaterials were presented (Khan, 2020). Full texts were then evaluated for relevance and methodological rigour after being screened in the first instance by title and abstract. Excluded were studies that did not meet these criteria.

5.2 Policy Document Analysis

A separate search was also conducted to extract policy documents from reliable sources such as European Commission, OECD, European Chemicals Agency (ECHA), and U.S. regulatory bodies including FDA. The safety and sustainability of nanomaterials and more specifically stimuli responsive “smart” nanomaterials was evaluated, to establish to what extent they are treated and considered in current guidelines and in regulatory frameworks, based on the analysis of these documents. Comparative analysis was undertaken, to draw similarities and differences from regional frameworks. The dynamic risk assessment methods as well as safe and sustainable by design (SSbD) principles in these policies were given special consideration (Report, European Commission, 2011; OECD, 2013).

5.3 Data Extraction and Synthesis

The data from the selected studies and policy documents were extracted using a standardised coding scheme. Study objectives, methodologies, quantitative results (e.g. energy consumption reductions, waste generation data) and main findings were recorded. To synthesise this information, it was then quantified wherever possible to allow for benchmarking for comparison of performance and qualitatively to identify themes that recur. Data was cross checked against original studies and high quality sources were retained (Salieri et al., 2018).

5.4 Conceptual Framework Development

An iteratively developed conceptual framework model was based on the synthesis of the literature and policy analysis. This model integrates four core dimensions: From global research networks, to policy and regulatory frameworks, to innovation practices and to sustainability outcomes. To further refine the model expert feedback was sought from several experts and the conceptual framework was cross validated with case studies (for e.g. those described by Mitra et al., 2021; Roco, 2004). Finally, the conceptual framework serves as the basis of discussion and is a visual and a theoretical representation of how global collaboration affects sustainable innovation.

6. Conceptual Framework Model

To understand how global collaboration enables green nanotechnology innovation, we propose a model of four interrelated dimensions. The model presented is assembled from insights from the literature and represents an analytical tool to depict the linkages between research collaboration, policy frameworks, innovation practices, and sustainability outcomes.

1. Global Research Networks:

Sharing best practices, collaborative standardization development of methodologies and joint risk assessment is done through international research networks. Through networks, such as the International Network4Sustainable Nanotechnology, diverse research groups are able to congregate data and resources together, increasing reliability and efficiency (Mitra et al., 2021; Roco, 2004). The development of decision support tools to quantify environmental impacts is supported by the collaborative exchange of technical information.

2. Policy and Regulatory Frameworks:

The European Green Deal, REACH and the Novel Food Regulation are the global regulatory frameworks that establish principles of safety and sustainability of nanomaterial products. However, existing definitions of nanomaterials are often static and may fail to capture dynamic, stimulus responsive properties of smart nanomaterials (European Commission, 2011; Kuzma & Roberts, 2016). Driver of sustainable innovation requires an adaptive policy framework attuned to emerging data from LCAs and risk assessment.

3. Innovation Practices:

Safe-and-sustainable-by-design (SSbD) principles should be implemented in the development of nanomaterials to impregnate environmental, health and economic parameters when early design is introduced. Because SSbD practices are based on working with green chemistry, a number of decision support tools have been developed to provide quantitative assessments of the energy consumption, waste generation, and total sustainability associated with processes (Soeteman Hernández et al., 2019; Van Harmelen et al., 2016).

4. Sustainability Outcomes:

The aspiration of the integrated approach is to make measurable improvements in sustainability outcomes. The potential outcomes of an effective system are reduced energy demand and less

greenhouse gas emissions, improved resource use, and corresponding economic benefits. Therefore, quantitative performance indicators, realised from LCAs and cost–benefit analyses, represent the evidence base needed to prove the success of evaluations for collaborative nanomaterial innovations (OECD, 2013; Salieri et al., 2018).

Figure 1. Conceptual Framework Model

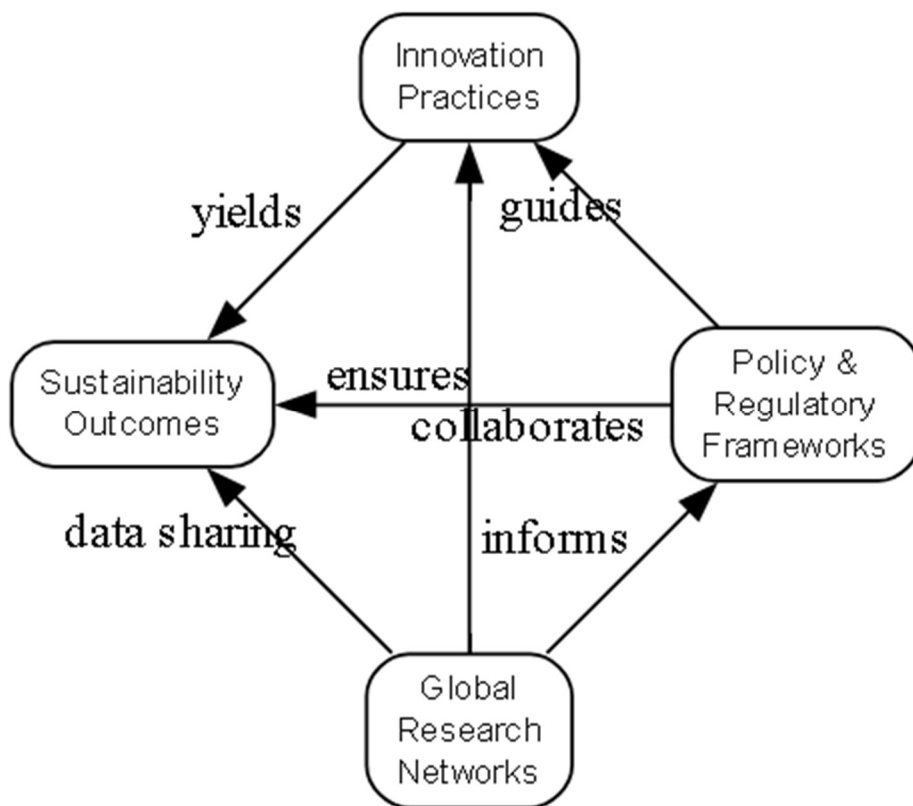


Figure 1. A Conceptual Framework Model to illustrate the interplay among the global research networks, the regulatory frameworks, innovation practices, and the sustainability outcomes in promoting global green nanotechnology.

7. Key Studies and Their Contributions

Table 1: Key Studies and Their Contributions

Study	Objective	Key Findings	Application Area	Link
Gottardo et al. (2021)	Examine safe and sustainable innovation in smart nanomaterials	Highlighted challenges in risk assessment and regulatory preparedness for dynamic materials	Nanomaterials applications	Link

Mitra et al. (2021)	Explore global collaboration in sustainable nanotechnology	Demonstrated that international networks enhance research reproducibility and harmonize regulatory standards	Sustainable nanotechnology	Link
Salieri et al. (2018)	Evaluate life cycle impacts of nanomaterials	Revealed significant quantitative gaps in LCA data and long-term environmental assessments	Lifecycle Assessment (LCA)	Link
Soeteman-Hernandez et al. (2019)	Develop a safe innovation approach and SSbD framework	Proposed integration of safe-by-design and regulatory preparedness to improve sustainability metrics	Policy and Regulation	Link
Van Harmelen et al. (2016)	Introduce LICARA NanoSCAN tool for sustainability evaluation	Developed a tool that provides quantitative metrics for assessing environmental, social, and economic impacts	Decision Support Tools	Link
Subramanian et al. (2010)	Classify active nanostructures based on stimuli-response	Developed a classification scheme for smart nanomaterials and emphasized the need for dynamic risk assessment models	Nanomaterial Classification	Link
Roco (2004)	Highlight the importance of unified research tools globally	Emphasized the need for transformative and unifying approaches in nanotechnology research	Global Collaboration	Link
Lu & Ozcan (2015)	Review eco-friendly synthesis methods for nanomaterials	Showed that green synthesis techniques can achieve energy efficiency and reduced waste compared to conventional methods	Green Synthesis	Link

Plazas-Tuttle et al. (2015)	Assess environmental implications of nanohybrids	Identified limitations of static risk models for materials with dynamic behavior, advocating for advanced risk assessment methods	Environmental Impact	Link
Yoshida & Lahann (2008)	Define and characterize smart nanomaterials	Detailed the stimuli-responsive properties and potential applications of smart nanomaterials	Smart Nanomaterials	Link

The summary of key studies that helped build our understanding of green nanotechnology and global collaboration is in table 1. Objectives, results and domain application of each study have been delineated to exemplify the contribution of collaborative research and policy to the sustainability outcome.

8. Discussion and Conclusions

As this review presents evidence, global collaboration is not only desirable, but it is crucial to further green technology by way of nanomaterials innovation. The integration of green chemistry and systems terminology creates a strong theoretical basis for designing nanomaterials with a smaller environmental footprint. Nevertheless, there exist key gaps in the literature, for which we highlight two critical ones: many studies describe promising synthesis techniques and performance enhancements (Lu et al., 2015; Gottardo et al., 2021), but relatively few studies quantitatively compare these advancements through the lifecycle of the material (Salieri et al., 2018). Traditional risk assessment and lifecycle analysis often are not dynamic and thus do not adequately capture the dynamic, stimuli responsive nature of smart nanomaterials (Subramanian et al., 2010; Plazas-Tuttle et al., 2015).

As illustrated by our review, the formation of global research networks standardises methodologies and shares important quantitative data through collaborative platforms (Mitra et al., 2021; Roco, 2004). By engaging in these collaborations, the research redundancies are cut down and tools such as LICARA NanoSCAN are further developed to supply empirical benchmarks for energy savings, waste reductions, and an overall measure of sustainability performance (Van Harmelen et al., 2016). In addition, case studies in smart food packaging and water treatment show how multinational collaboration can lead to real economic and environmental advantages like, for example, reduction in food spoilage and increased water treatment efficiency (Brockgreitens & Abbas, 2016; European Commission, 2009).

Still, there are many challenges. This review demonstrates that the dynamic properties of smart nanomaterials exceed the boundaries set by existing regulatory statutes, which rely on static definitions (European Commission, 2011, Kuzma & Roberts, 2016). Currently, many regulatory assessments are not yet in a position to track time dependent toxicity and environmental impact. Consequently, if regulators are to adequately control the risks physical nanomaterials pose, a shift toward a dynamic, time dependent risk assessment model is needed. Meanwhile, initiatives like the European Green Deal and REACH have established a base of awareness of the safety and

sustainability focus, but differences between regional approaches to regulation impede global market harmonization (OECD, 2013).

In this context, the Safe & Sustainable by design (SSbD) framework emerges as one of the most crucial strategy. Anticipating future advancements, the design for safety and sustainability (SSbD) integrates safety and sustainability at the earliest stages of production supported by quantitative decision support tools and rigorous LCA to ensure new nanomaterial products have positive effects on both environmental outcomes and economic performance (Soeteman-Hernandez et al., 2019). As a result, future work needs to further refine SSbD methodologies, and to encourage more dialogue between policymakers, researchers and industry actors for the development of harmonized international standards.

Lastly, the route to the promotion of green technology through global co operation in nanomaterial innovation involves tackling both technical and regulatory obstacles. Through green chemistry, dynamic risk modelling, and international collaboration, nanomaterial synthesis can evolve from a technical innovation to one that is environmentally sustainable and economically viable. To overcome the limitations of static risk assessments, overcoming the limitations of static risk assessments such as those from static risk assessments and enable smart nanomaterials to allow smart nanomaterials to deliver on their promise in building a climate neutral, circular future, it is crucial to develop global research networks and harmonised regulatory frameworks. Future work should include the development of time dependent risk assessment tools, more quantitative evaluations throughout the lifecycle of nanomaterials, and regulation standard harmonization. Coordination of such efforts can thus make nanomaterial innovation a central driver toward sustainable development.

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