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Responsible innovation in nanotechnology: response to grand societal challenges

Sanduni Dabare, †[a] Sisitha Rajapaksha †*[b] and Imalka Munaweera *[a]

The biosphere of the Earth is confronted with enormous sustainability challenges. An essential method for addressing these challenges is through innovation. Grand Societal Challenges (GSCs) are intricate, multi-faceted issues that necessitate collaborative efforts from many stakeholders, including public, corporate, and non-profit sectors, for effective resolution. Responsible innovation (RI) is a framework that facilitates the governance and assessment of innovations regarding their possible detrimental effects and beneficial impacts on societal concerns. Insights from the natural sciences can facilitate the evaluation of technological innovation possibilities, operationalize their contributions to the resolution of GSCs, illustrate system interdependence, and quantify the effects of innovation on GSCs, including both the potential detriments and advantageous societal impacts of business innovation. There is limited research in nanotechnology on RI addressing Grand Societal Challenges. This study aims to thoroughly examine the existing literature on responsible innovation, nanotechnology, and Grand Societal Challenges, while proposing avenues for further research. The PRISMA framework is employed to systematically select articles from the Scopus and Web of Science databases in this conceptual review. The search terms used were "Nanotechnology," "Responsible Innovation," and "Grand Societal Challenges". The systematic selection process, in conjunction with the application of VOSviewer software for keyword co-occurrence analysis, not only identified prospective under-explored research areas but also highlighted valuable insights, thereby paving the way for future development in these critical fields. The study revealed eight innovative clusters with deep insights into the research. Future research efforts may focus on RI in nanotechnology in addressing GSCs. This is a pioneering study that integrates RI, nanotechnology, and GSCs.

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1 Introduction

Grand Societal Challenges (GSCs) are widely recognized as large-scale, complex problems that require collective action across public, private, and non-profit sectors. For example, Voegtlin *et al.* (2022) define GSCs as "complex, multi-level, multi-dimensional problems that require concerted efforts by various actors".[1] These cover various areas. Major examples include climate change and environmental degradation, global public health issues (like pandemics and healthcare equity), demographic changes (such as aging populations),[1,2] energy and resource sustainability (secure, clean energy and materials),[1] socio-economic inequality and poverty, rapid digital transformation and technological disruption (*e.g.*, AI, automation, ICT).[2]

[a]Department of Chemistry, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda (10250), Sri Lanka. E-mail: imalka@sjp.ac.lk; dabaresanduni@gmail.com

[b]Department of Management Studies, Faculty of Indigenous Social Sciences and Management Studies, Gampaha Wickramarachchi University of Indigenous Medicine, Yakkala (11870), Sri Lanka. E-mail: sisitha@gwu.ac.lk

† Equally contributed.

Each of these issues carries significant social, moral, and financial implications.[1,2] GSCs are intricately aligned with international frameworks such as the United Nations Sustainable Development Goals. Importantly, GSCs establish the context and set the priorities for current innovations; solutions are anticipated to be not only technically effective but also socially responsible and sustainable.[3]

Responsible Innovation (RI) is a developing governance approach created to guide science and technology toward socially beneficial goals.[4] It builds on ideas like anticipatory governance and upstream public involvement, viewing innovation as a socio-technical process rather than just a market-driven activity one.[5] Stilgoe *et al.* (2013)[6] famously summarize RI as "taking care of the future through collective stewardship of science and innovation in the present". In practical terms, RI is based on four key principles – anticipation of impacts, inclusion of diverse stakeholders, reflexivity about underlying assumptions, and responsiveness to societal needs – along with related values like transparency and sustainability.[7] The RI framework recommends incorporating ethical reflection, risk assessment, and stakeholder input into R&D to ensure emerging technologies match public values.[8] As Voegtlin *et al.*

(2022)[1] explain, RI provides a framework for the governance and evaluation of innovations about their potential harmful consequences and positive contributions to societal challenges.

Nanotechnology, the science and engineering of manipulating matter at the atomic, molecular, and supramolecular scale, typically at dimensions less than 100 nanometers is widely recognized as a transformative, versatile technology.[9,10] Governments and international agencies highlight its capacity to drive breakthroughs by enabling the development of new materials, processes, and products. Recent reviews report its applications spanning medicine, electronics, energy, environmental management, and materials science. In medicine, for example, nanocarriers such as liposomes, dendrimers, micelles and polymer-based nanoparticles have been developed for advanced drug delivery systems, improving targeting, reducing side effects, and enabling payloads of poorly soluble drugs.[11–13] In the energy sector, nanoscale materials and nano-enhanced architectures are used to produce ultra efficient solar cells, improve light absorption, reduce losses, and enable next generation designs such as quantum dot solar cells and perovskite photovoltaics.[2,10,14] Moreover, nanomaterials are being engineered to yield self healing, durable materials (for coatings, composites, *etc.*) and environmental remediation, advanced sensors, and novel smart materials that respond dynamically to their environment.[11,15] The capacity for transformation inherent in this field suggests significant relevance to numerous GSCs. For instance, research focusing on Society 5.0 scenarios indicates that nanomaterials have the potential to facilitate the digital revolution through their applications in Internet of Things (IoT) sensors, robotics, and autonomous vehicles. Furthermore, these materials contribute to advancing environmental sustainability by enabling solutions such as water purification, carbon dioxide reduction, and recycling.[16] Additionally, nanomaterials play a vital role in the healthcare sector through the development of wearable biosensors and advancements in regenerative medicine.[2] Nanotechnology already underpins many innovations in energy efficient electronics, advanced catalysts, and precision medicine, all of which could help address challenges like climate change, resource scarcity, and aging related health care.[17]

At the same time, nanotechnology's novelty introduces unique risks and ethical considerations. Its key features such as the large surface area, reactivity, and mobility of nanoparticles may cause unforeseen health and environmental effects.[17] Early social science discussions on nanotech explicitly viewed it as an opportunity to ‘get things right’ and ‘avoid past mistakes’ by integrating ethics and public engagement into research efforts.[18] Consequently, agencies like the U.S. National Nanotechnology Initiative focus on nanomaterial safety research by funding studies on environmental, health, and safety (EHS) implications[9] to promote responsible development.[9] Essentially, nanotechnology highlights the importance of RI, as it is a developing area characterized by significant uncertainty, complexity, and public debate.[5] Responsible governance is seen as essential to ensure that its development contributes positively to grand challenges rather than creating new problems.[19] It is essential to incorporate diverse stakeholder perspectives and foster civic engagement, particularly when advancing innovations in areas that are often met with societal skepticism such as synthetic biology, nanotechnology, genetic engineering, automation and robotics, and artificial intelligence.[1,20]

To navigate this terrain, we pose the central research question: *“How is responsible innovation in nanotechnology being conceptualized and implemented to address Grand Societal Challenges?”*. This question seeks to encompass both theoretical and practical dimensions, namely how scholars and stakeholders conceptualize RI in nanotechnology and what measures or policies are enacted within the RI framework to address GSCs. Addressing this question is timely because nanotechnology research is growing rapidly, and its applications are increasingly related to critical areas such as clean energy, health, and digital infrastructure.[2] Meanwhile, the RI literature continues to expand, though scholars observe significant variation in RI definitions and practices across different contexts.[5] Some studies have started to explore responsible approaches in specific nanotech areas, such as RI in nano-enabled agriculture and food systems.[21] However, there is no comprehensive review that maps the overall landscape of RI in nanotechnology in relation to grand societal challenges. Therefore, the main goal of this research is to review existing literature on RI in nanotechnology concerning Grand Societal Challenges (GSCs) and to identify future research directions.

Indeed, recent commentary explicitly calls for connecting RI scholarship with GSCs.[1] In this context, a systematic review is necessary to gather and analyze the existing literature on responsible nanotechnology to clarify how RI is framed, what practices or policies are emerging, and where gaps still exist. Using a rigorous review process, this work will lay a foundation for understanding how nanotechnology innovation can be responsibly directed toward the goals of sustainability, public health, equity, and other major challenges.

2 Methodology

2.1 Study selection and process methods

This study followed the Systematic Literature Review (SLR) methodology. The SLRs must follow the PRISMA framework as recommended guidelines for planning, conducting, and reporting in an SLR.[22,23] Thus, complying with the PRISMA requirements, we prepared a protocol at this study's planning level, and the content of it is given in Table 1. It includes the article selection method, search terms, inclusion criteria, analysis methods, and reporting structure. According to Table 1, the article selection method and reporting structure were designed based on the PRISMA guidelines. The search terms and article inclusion criteria were decided at the planning level, outlined in Table 1. This search was conducted in May 2025.

As noted in Table 1, the article selection was performed by the PRISMA requirements, for which the PRISMA flow diagram has been developed. It has three steps: “identification,” “screening,” and “included.” Fig. 1 shows how these steps were followed in the study. In the “identification,” the search terms were: “Responsible Innovation” AND “Nanotechnology” AND “Grand Societal Challenges”. High-quality research articles were selected for this study by retrieving them from the Scopus

Table 1 Inclusion and exclusion criteria – responsible innovation, nanotechnology and grand societal challenges[a]

Article selection method	PRISMA guidelines[1]
Search strings	"Responsible Innovation", "Nanotechnology" and "Grand Societal Challenges"
Inclusion criteria	(1) Year range: 2009–2024
	(2) Subject area: all
	(3) Language of article: English
	(4) Keywords: included all
	(5) Source type: academic journals
	(6) Type of study: quantitative
	(7) Methodological quality: quantitative and qualitative
Databases	Scopus and web of science
Analysis method	Keyword co-occurrence analysis
Reporting structure	PRISMA guidelines
Search criteria	"Responsible Innovation" AND "Nanotechnology" AND "Grand Societal Challenges"
Whom do the screening and eligibility checking?	Authors have screened independently

[a] Source: authors developed,[1] PRISMA – preferred reporting items for systematic reviews and meta-analyses.

and Web of Science databases. To sift through articles, a combination of automatic and manual screening methods was used to remove items that were not relevant. This analysis exclusively focused on journal articles authored in the English language. Systematic reviews strongly recommend using journal papers because of their reliability, which stems from a rigorous peer-review process.

2.2 Article risk of bias assessment

The quality of a review suffers due to researcher bias in article selection and analysis. The selection bias can be minimized by following a review protocol, a systematic, objective article selection procedure,[24] and conducting a parallel independent quality assessment of publications by two or more reviewers. Moreover, a preliminary protocol design that predetermines the analysis procedures can help to reduce analysis bias.[25] Thus, those procedures were followed to eliminate bias in article selection and analysis.

2.3 Methods of analysis

The analysis method used was a bibliometric analysis. It was performed through the VOSviewer. It is a quantitative method

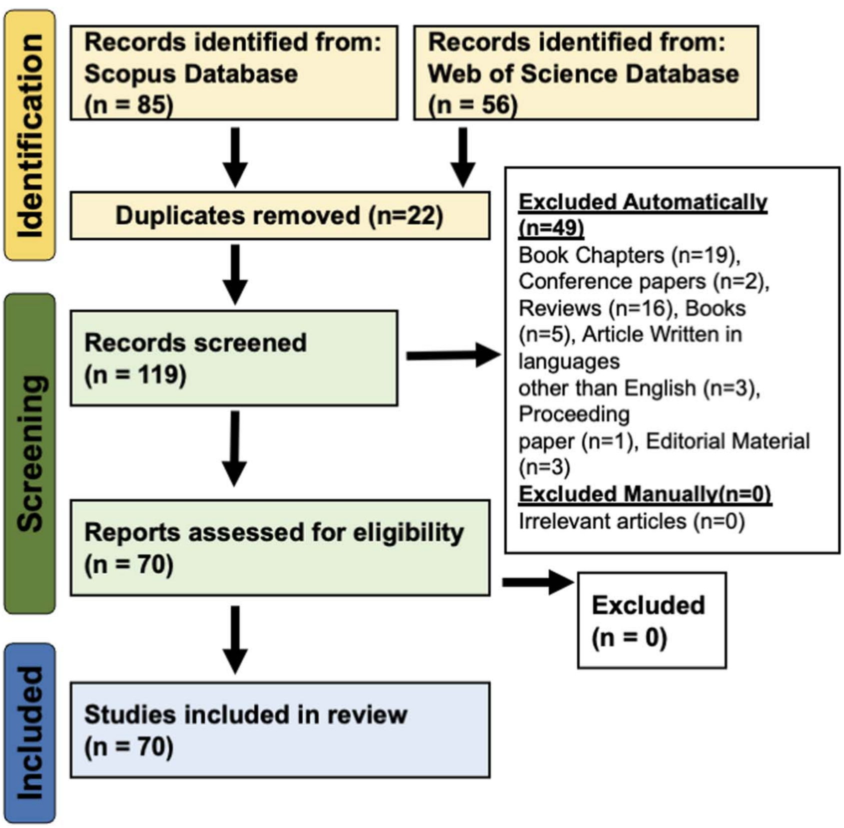

Fig. 1 PRISMA flow diagram source: authors developed.

for analyzing scientific activity in research. Among various bibliometric analyses, the keyword co-occurrence analysis is vital to identify the keywords used in article abstracts. The VOSviewer extracted the keyword co-occurrence data, creating keyword co-occurrence network visualization. This technique divides the term into several clusters. So that the themes represented by each cluster can be discovered.

According to the user manual of the VOSviewer software, the scientific maps analyze the article's structure, development, and relevant players.[23] The maps are generated through bibliometric networks, and there are various units of analysis, such as keywords, terms, authors, citations, country of publication, or source types. The most common unit of analysis is the keywords that reflect the main content of an article. In the case of finding the common or most minor areas of investigation, this co-occurrence of keywords in articles is taken as the unit of analysis. Thus, the links of such networks can be created using the co-occurrence relationship of such keywords in the articles. VOSviewer visualizes them as "keyword co-occurrence network visualization". After relativizing the interconnection of keywords, meaningful information about the content in the keyword co-occurrence network visualization can be obtained. This process is done by normalizing the keyword co-occurrence network visualization. As a result, by default, the VOSviewer employs association strength normalization and generates a network in a two-dimensional space. In that space, significantly linked keywords represented by nodes are found near one another, whereas less significant ones are found far away.[26] The VOSviewer then distributed the nodes to a network of clusters, with highly correlated nodes assigned to the same cluster VOSviewer uses colors to denote the cluster assigned to a node. As a result, a cluster may indicate a common theme.[27]

3 Results and findings

3.1 Study selection

Following the PRISMA guidelines, a comprehensive article selection process was undertaken to identify relevant literature on "Responsible Innovation," "Nanotechnology," and "Grand Societal Challenges" (combined with AND). This focus ensured that we captured studies explicitly linking all three domains. The initial search across Scopus and Web of Science databases yielded a total of 141 articles (Scopus: 85; Web of Science: 56). After automatic exclusion and removing 22 duplicate entries, 70 records were screened.

Automatic exclusion was applied based on the following criteria: book chapters ($n = 19$), conference papers ($n = 2$), reviews ($n = 16$), books ($n = 5$), articles not written in English ($n = 3$), proceeding papers ($n = 1$), and editorial materials ($n = 3$). No articles were excluded manually for irrelevance at this stage. As a result, 70 articles proceeded to the eligibility assessment stage. The search was confined to peer-reviewed journal articles published in English from 2009 to 2024, a period during which the concepts of Responsible Research and Innovation (RRI) gained notable prominence. Empirical studies, whether quantitative or employing mixed methods, were mandated to emphasize measurable evidence; as detailed in Table 1, quantitative methodologies were predominantly chosen to uphold methodological rigor. All 70 articles meeting these criteria were included in the analysis. The screening process involved independent dual reviewers to minimize selection bias. The commencement year of 2009 correlates with the advent of formal RRI discourse within policy frameworks, and a focus on journal publications, excluding grey literature, ensures reliance on peer-reviewed and credible sources. The entire process is illustrated in Fig. 1.

3.2 Study characteristics

The 70 publications included in the study span 22 countries and 32 journals. Table 2 shows the 32 most relevant journals. The *Journal of Responsible Innovation* is the top journal, with 14 articles, 146 citations, and a total link strength of 312. It is followed by *NanoEthics* with 10 articles and *NanoImpact* with 5 articles. Fig. 2 illustrates the contribution by country: a few nations lead with the highest output, 20 papers shown in light green, while others are represented in blue (16), yellow (6), dark green (3), and brown (1). This distribution indicates that most RI-nanotech research is concentrated in a small number of research hubs, emphasizing the need to promote more balanced global research participation. Regions such as Africa, Latin America, and parts of Asia seem underrepresented, highlighting opportunities to enhance capacity and foster collaboration in these areas.

The VOSviewer bibliographic coupling map (Fig. 3) illustrates the research collaboration and citation relationships among countries based on shared references in scientific publications. The network is divided into distinct color-coded clusters, each representing groups of countries with strong bibliographic connections. The red cluster, primarily composed of Central and Western European countries such as Germany, the United Kingdom, Switzerland, and Italy, indicates dense collaboration within Europe. The green cluster includes globally prominent research contributors like the United States, the Netherlands, China, India, and Canada, reflecting strong international cooperation and high research output. Notably, Spain forms a separate blue cluster, suggesting its role as a bridge between European and international collaborations. The size of each node corresponds to the volume of research output or strength of bibliographic links, with larger nodes such as the United States and Netherlands highlighting their central roles in global research networks. The thickness of the connecting lines signifies the intensity of bibliographic coupling, with thicker lines indicating stronger citation overlaps. Overall, the map emphasizes the interconnected nature of global scientific collaboration and the central roles played by key research-intensive nations.

3.3 Results of studies

This section reports the findings aligned with the research objectives. The findings were developed using keyword co-occurrence analysis. The two forms of keyword co-occurrence,

Table 2 List of 32 most-relevant journals. The *Journal of Responsible Innovation* leads with 14 articles (146 citations; total link strength 312), followed by *NanoEthics* (10 articles) and *NanoImpact* (5 articles). VOSviewer defines total link strength in this bibliometric context as the sum of all bibliographic coupling links for that journal – a proxy for how central or interconnected a journal is in the literature network. The very high link strengths for *Journal of Responsible Innovation* (312) and *Research Policy* (238) indicate these outlets serve as hubs in the RI-nanotechnology discourse. For example, *Research Policy* has only 3 documents but 200 citations and a link strength of 238, reflecting its influence. The cluster of social science journals (*Soc. Stud. Sci.*, Public Understanding of Science) also appears, albeit with lower output[a]

Source	Documents	Citations	Total link strength
Journal of Responsible Innovation	14	146	312
Research Policy	3	200	238
Nanoethics	10	97	185
Science and Public Policy	1	34	169
NanoImpact	5	43	168
Science and Engineering Ethics	3	106	161
Journal of Nanoparticle Research	2	8	122
Risk Analysis	3	160	119
Technology Analysis and Strategic Management	2	25	117
Social Studies of Science	1	505	104
Bulletin of Science, Technology and Society	2	14	99
Journal of Responsible Technology	1	10	79
Futures	3	14	77
Asian Biotechnology and Development Review	1	2	71
Environmental Science and Policy	1	2	71
Social Epistemology	1	51	57
Chem-Bio Informatics Journal	1	3	55
Journal on Chain and Network Science	1	37	47
International Journal of Technoethics	1	11	46
Integrated Environmental Assessment and Management	1	20	42
Global Food Security	1	398	24
Public Understanding of Science	2	115	19
Scientometrics	1	4	15
Toxicology	1	201	15
Ecotoxicology and Environmental Safety	1	88	3
Etica e politica	1	3	2
Planet Earth	1	3	1
Computers in Human Behavior	1	0	0
Giornale Italiano di medicina del Lavoro	1	0	0
Historia Ciencias Saude-manguinhos	1	0	0
People and Nature	1	0	0
Technology Analysis & Strategic Management	1	0	0

[a] (Source documents-number of included articles; citations-total citations accrued; total link strength-sum of bibliographic coupling links (from VOSviewer) for each journal.) The search was conducted in May 2025.

"network visualisation" and "density visualisation" were utilized in the study. The keywords co-occurrence network visualisation, in particular, addressed the first objective: finding the current knowledge of RI in nanotechnology in the context of addressing GSCs. The keyword co-occurrence density visualisation addressed the second objective: finding the areas where empirical research on RI in nanotechnology is lacking concerning GSCs.

3.3.1 Cluster analysis

Cluster 1 – value-sensitive design in advanced nanotechnologies. Cluster 1 focuses on embedding ethical and human values into advanced technologies like nanotechnology, engineered nanomaterials, and AI. The value-sensitive design (VSD) framework helps align technological development with societal needs, making sure innovations are both effective and fair.[28–30]

RI requires anticipating societal implications and embedding moral responsibility in the development process. VSD provides a concrete method for achieving this in artificial intelligence (AI) and nanotech. The engineered nature of nanomaterials calls for proactive ethical foresight, especially when intersecting with intelligent systems.[31,32]

Cluster 2 – collaborative ecosystems for emerging technologies. The rise of disruptive innovations in nanotech demands collaboration across disciplines and sectors to create a unified innovation ecosystem.[32] Promoting shared learning among actors encourages reflexivity and responsiveness as new technologies develop.[33,34]

The RI framework depends on adaptive governance, co-creation, and inclusive learning. These processes are critical for managing uncertainty and complexity in emerging technologies such as nanotech. Cross-disciplinary collaboration becomes a mechanism to promote sustainable and socially attuned outcomes.[35,36]

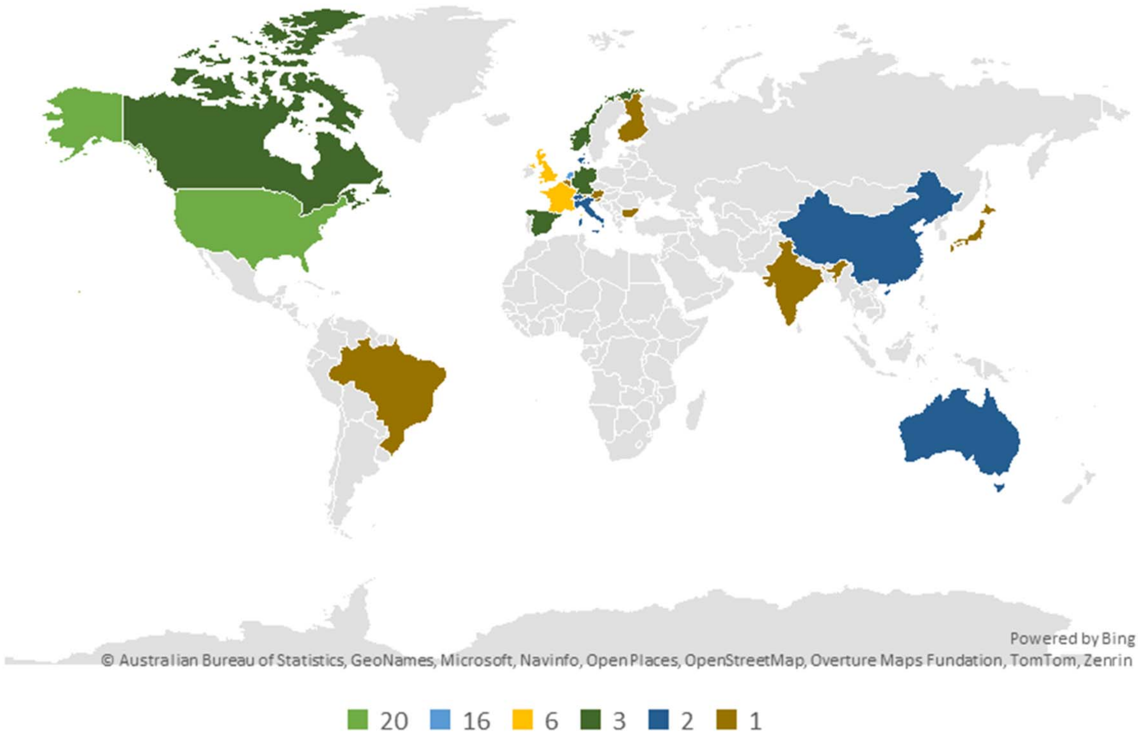

Fig. 2 Global distribution of RI-nanotechnology studies (countries shaded by number of publications). The color scale (light green highest) shows a few nations dominating publication output (20 and 16 publications in the top colors). This unequal geography – coupled with the fact that 70 papers came from only 22 countries – suggests a need to build research capacity and collaboration in underrepresented regions.

Cluster 3 – governance mechanisms for sustainable innovation. To foster responsibility, innovation must be guided by ethical principles, transparency, and inclusiveness. Governance and intervention research inform frameworks for assessing progress. RI practices support this process, ultimately aiming for sustainability as a long-term objective.[36–41]

Theoretical frameworks such as anticipatory governance and transition management are central here. These guide responsible responses to uncertainty and risk in nanotech applications, ensuring innovations do not outpace societal readiness or acceptance.[42,43]

Cluster 4 – managing risks through scientific assessment. The rapid progression of nanoscience and nanomaterials demands

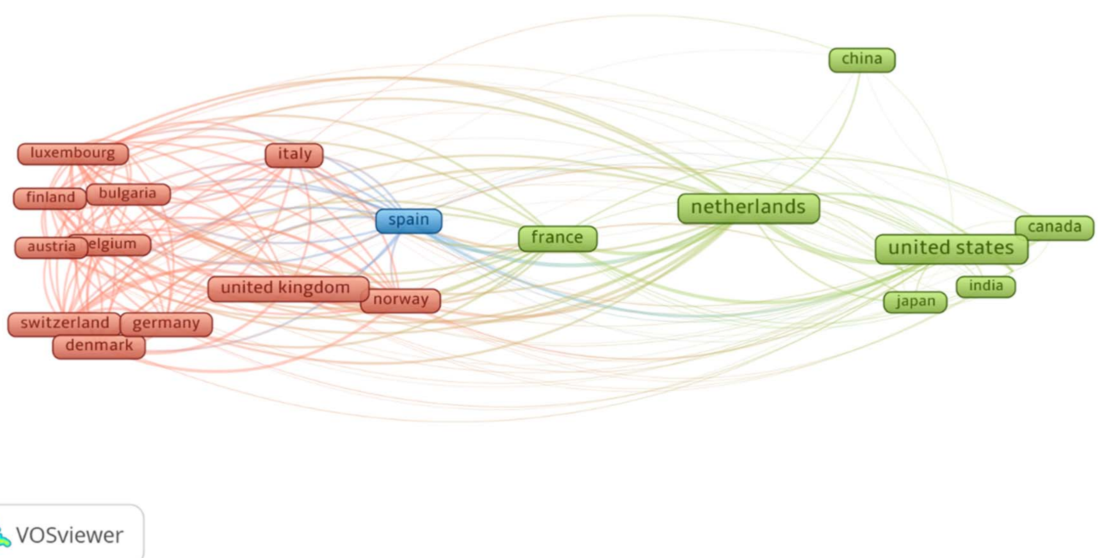

Fig. 3 Bibliographic coupling map of countries. Nodes represent countries, colored by cluster of co-citation links node size reflects publication volume and link strength. Thicker lines indicate stronger citation overlaps, highlighting tightly-knit research partnerships.

a structured approach to risk analysis and technology assessment. Understanding risks at the molecular level allows for proactive mitigation strategies.[33,40,44,45]

Ensuring the safety, transparency, and public trust in nanotech necessitates robust methodologies for risk and impact assessment. RI encourages early identification of unintended consequences.[32,46]

Cluster 5 – embedding ethical norms in scientific practice. The core of RI lies in practicing ethical leadership and conducting responsible research and science that aligns with societal values. Engaging with the societal and ethical implications of nanotech strengthens democratic legitimacy.[47–51]

This cluster aligns with normative theories of ethics in science and innovation, encouraging foresight, inclusiveness, and reflexivity. Ethical leadership is central to navigating dilemmas and guiding innovation with integrity.[52,53]

Cluster 6 – domain-specific responsible applications. Nanotechnology applications in food and agriculture and nanomedicine present vast benefits but also require targeted regulation and active stakeholder engagement. These domains demand careful oversight to ensure safety and public acceptability.[5,54–56]

RI here focuses on application-level strategies, regulatory science, participatory governance, and translational research to balance innovation with public interest. Effective regulation is dynamic and co-developed with stakeholder input.[57,58]

Cluster 7 – socio-technical integration for innovation justice. Fostering interdisciplinarity enables holistic understanding and socio-technical integration, ensuring science and technology are deeply connected to society. Such integrative approaches are key to aligning research with real-world problems.[50,59]

This cluster highlights the importance of systems thinking and interdisciplinary collaboration. RI frameworks like STIR (Socio-Technical Integration Research) and RRI operationalize these ideals.[60]

Cluster 8 – public participation in nanotechnology futures. Public engagement is a cornerstone of democratic innovation. In the context of nanotechnology, public input is crucial for legitimacy, trust, and aligning innovation with societal values.[61,62]

Theoretical foundations such as deliberative democracy and citizen science emphasize inclusion. In practice, public engagement influences governance, shapes funding priorities, and fosters social acceptability.[63,64] Table 3 represent thematic Clusters of RI in nanotechnology: keywords, internal dynamics, and cross-cluster interrelations.

Each cluster corresponds to established RI concepts, such as those related to VSD, governance, and public engagement. For instance, Cluster 6, which focuses on domain-specific applications, indicates that nanotechnology in food, agriculture, and medicine is being examined through the lens of RI. However, no cluster explicitly addresses "Grand Societal Challenges" or similar terms. In the keyword network, terms like "climate," "sustainability," and specific words related to the Sustainable Development Goals (SDGs) fail to form a distinct cluster. This absence is particularly noteworthy given our search focus, as it confirms that the explicit connection between RI/nanotechnology research and global challenges is minimal.

The cluster analysis shows that RI in nanotechnology is mainly understood in terms of ethics, governance, risk, and stakeholder engagement, rather than within the framework of grand challenges. This finding, that the current literature on RI and nanotechnology lacks an explicit focus on Grand Societal Challenges, is a key takeaway from our study. It highlights the novelty of our contribution in identifying this gap and sets the stage for the following discussion.

3.3.2 Network visualization. The network visualization map generated using VOSviewer (Fig. 4) reveals the structural relationships among key concepts related to nanotechnology and RI. Each keyword is represented as a node, where the size of the label and circle reflects its frequency or weight in the dataset. "Nanotechnology" emerges as the most central and highly weighted term, indicating its dominant presence and connectivity across thematic areas. The color coded clusters highlight distinct yet interrelated domains: the red cluster centers on technical aspects such as AI and engineered nanomaterials; the blue cluster captures the ethical and policy-oriented dimensions, including RI, governance, and sustainability; while the green and purple clusters emphasize innovation systems and ethical leadership, respectively. The proximity of terms such as "responsible innovation," "value sensitive design," and "public engagement" to "nanotechnology" underscores a growing convergence between scientific advancement and social responsibility. Moreover, links to fields like food and agriculture and nanomedicine suggest a multidisciplinary application of nanotechnology. This visualization affirms the critical importance of integrating ethical, societal, and governance considerations in the development and application of emerging technologies.

3.3.3 Density visualization. The item density visualization generated by VOSviewer (Fig. 5) illustrates the conceptual structure of research surrounding RI and nanotechnology. In this map, the most densely populated and interconnected areas are highlighted in red and yellow, indicating high-frequency and heavily weighted keywords. Notably, "responsible innovation" and "nanotechnology" appear as central terms, each surrounded by clusters of closely related keywords. "responsible innovation" is linked with terms such as "governance," "sustainability," and "public engagement," suggesting a strong focus on ethical and societal aspects of innovation. Similarly, "nanotechnology" is closely associated with "artificial intelligence," "engineered nanomaterials," and "value-sensitive design," reflecting its intersection with emerging technologies and ethical considerations. In contrast, the blue areas represent lower-density regions with fewer co-occurring terms, such as "technology assessment," "ethical leadership," and "innovation ecosystem," which may represent more specialized or emerging research themes. Future research may focus on an area in which the three search keywords, Responsible Innovation, Nanotechnology, and Grand Societal Challenges, are intersected. It is evident that the keyword, Grand Societal Challenges, does not appear in the density visualization map, which indicates the need for further research related to this domain. Overall, the

Table 3 Thematic clusters of responsible innovation in nanotechnology in addressing grand societal challenges: keywords, interrelations (within cluster), and interrelations (across clusters)

Cluster	Keywords	Interrelations (within cluster)	Interrelations (across clusters)
C1 – value-sensitive design (VSD) in advanced nanotechnologies	Artificial intelligence, engineered nanomaterials, nanotechnology, value-sensitive design	VSD guides the ethical development of AI and nanomaterials within nanotechnology[28–30]	Supports ethical leadership (C5), relies on interdisciplinarity (C7), and benefits from public engagement (C8)
C2 – collaborative ecosystems for emerging technologies	Boundary spanning, emerging technologies, innovation ecosystem, shared learning	Collaboration across sectors facilitates the development of emerging nanotechnologies[33,34]	Enhances stakeholder engagement (C6), informs governance practices (C3), and strengthens science and society connections (C7)
C3 – governance mechanisms for sustainable innovation	Governance, intervention research, responsible innovation, sustainability	Governance structures shape responsible and sustainable innovation through empirical intervention studies[36–40]	Intersects with regulation (C6), reinforces risk analysis (C4), and depends on ethical leadership (C5)
C4 – managing risks through scientific assessment	Nanomaterials, nanoscience, risk analysis, technology assessment	Risk assessment and tech evaluation are grounded in scientific understanding of nanomaterials[33,40,44,45]	Informs governance (C3), underpins responsible science (C5), and shapes regulation strategies (C6)
C5 – embedding ethical norms in scientific practice	Ethical leadership, responsible research, responsible science, societal & ethical implications	Ethical frameworks guide researchers in addressing societal impacts[47–51]	Connects to VSD (C1), guides public engagement (C8), and shapes socio-technical integration (C7)
C6 – domain-specific responsible applications	Food & agriculture, nanomedicine, regulation, stakeholder engagement	Regulation and stakeholder input are vital in high-impact sectors like food and medicine[5,54–56]	Dependent on risk analysis (C4), informed by shared learning (C2), and guided by ethical principles (C5)
C7 – socio-technical integration for innovation justice	Interdisciplinarity, science & society, socio-technical integration	Collaboration and integration ensure that innovation is socially embedded[50,59]	Foundation for value-sensitive design (C1), promotes shared learning (C2), and supports public engagement (C8)
C8 – public participation in nanotechnology futures	Public engagement	Public involvement legitimizes and informs responsible innovation pathways[61,62]	Cross-cuts all clusters, supports governance (C3), ethical leadership (C5), and sectoral stakeholder engagement (C6)

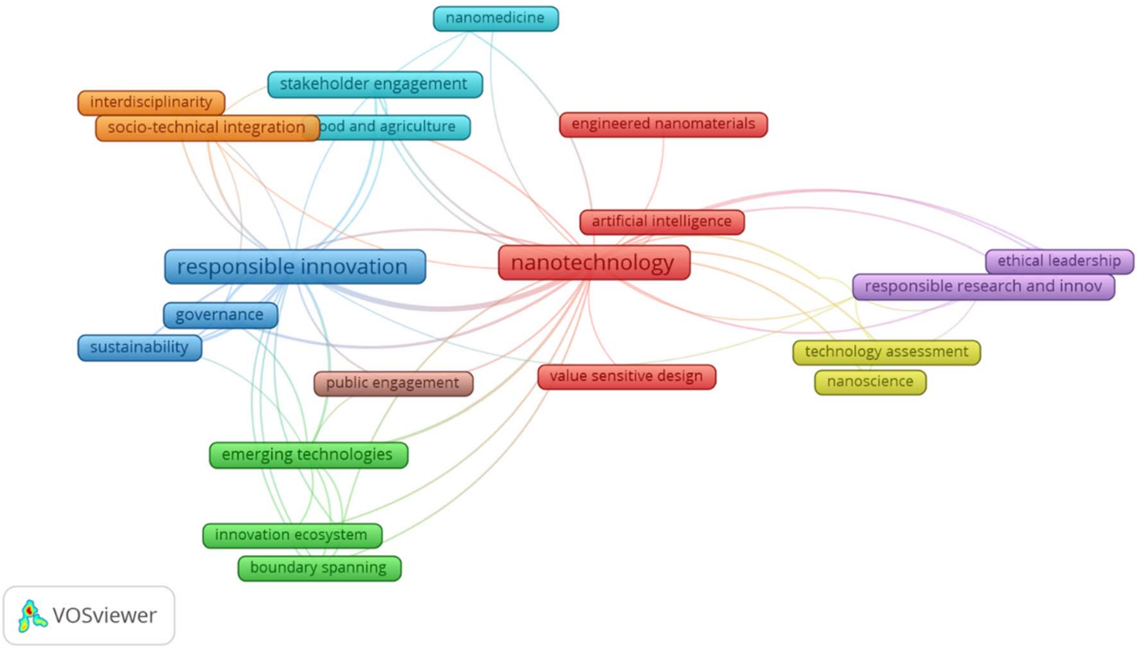

Fig. 4 The network visualization map generated using VOSviewer.

visualization reveals that RI and nanotechnology are the dominant focal points in the research landscape, with various interdisciplinary and ethical dimensions contributing to the broader discourse.

4 Discussion

The systematic review of 70 peer-reviewed articles reveals a complex but fragmented landscape in the intersection of RI, nanotechnology, and GSCs. While the field has demonstrated

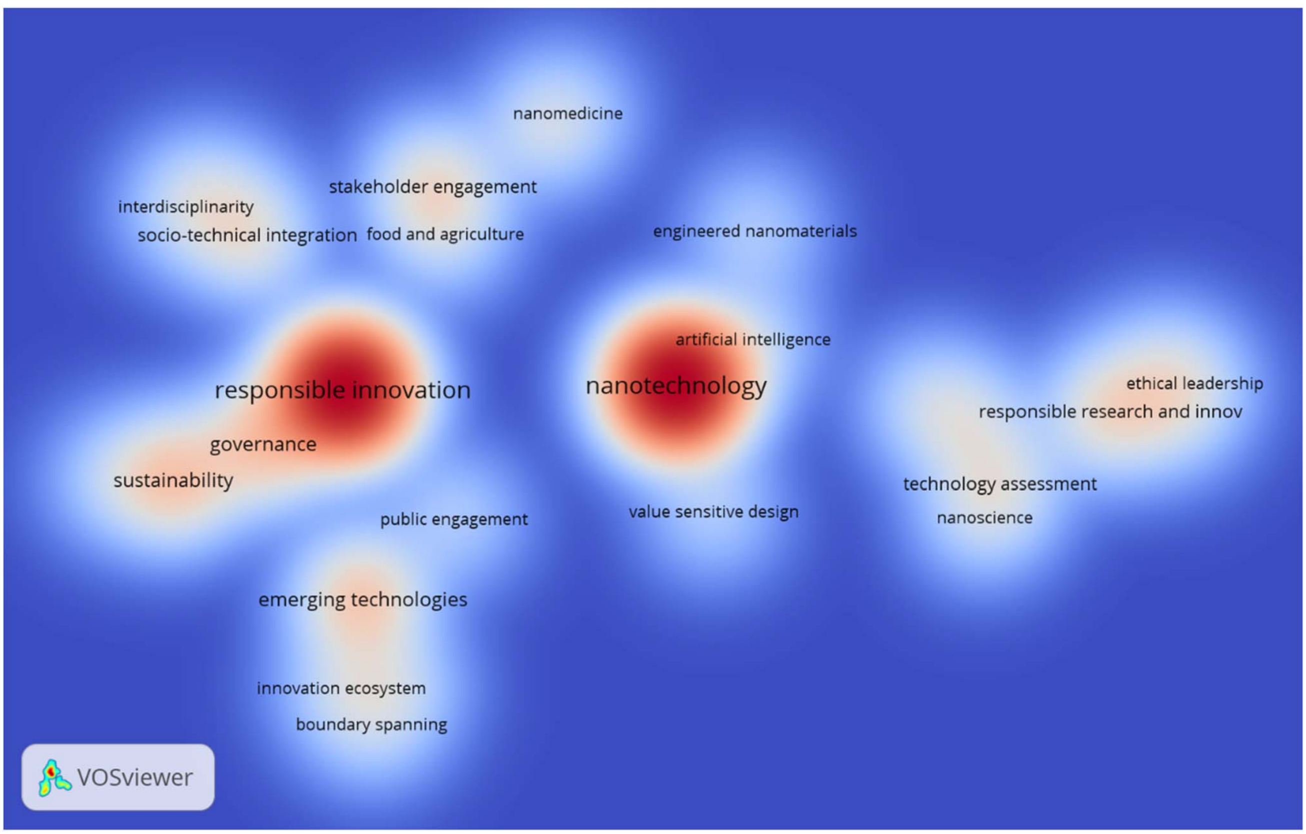

Fig. 5 Density visualization.

substantial growth since 2009, coinciding with the formal emergence of RRI discourse in policy frameworks, several critical patterns emerge that warrant detailed examination.

The geographic distribution of research reveals a stark concentration of scholarly activity in a limited number of research hubs. With only 22 countries contributing to the 70 publications analyzed, the global research landscape exhibits significant inequality. The dominance of Western European countries, particularly Germany, the United Kingdom, Switzerland, and Italy, and North American institutions, the United States, Canada, alongside emerging contributions from China, India, and the Netherlands, highlights a concerning pattern of research concentration in already well-resourced academic systems. This echoes critiques in the literature: Pandey (2024)[65] notes that mainstream RRI has a fixation on Europe as its Centre, which can alienate the Global South perspective. In other words, the skewed country distribution we found parallels concerns that RRI research remains largely Euro American in orientation.

This geographic imbalance has significant implications for developing truly global approaches to responsible nanotechnology innovation. The underrepresentation of regions such as Africa, Latin America, and large parts of Asia indicates that local contexts, cultural values, and region specific societal challenges might not be sufficiently reflected in current RI frameworks. Since many of the most urgent Grand Societal Challenges including climate change adaptation, food security, and access to clean water disproportionately impact these underrepresented regions, this geographic bias is a fundamental limitation in the field's ability to address global challenges comprehensively.

The analysis of publication venues reveals the emergence of specialized journals as key knowledge hubs. The dominance of the *Journal of Responsible Innovation* (14 articles, 312 total link strength) and the significant influence of *Research Policy* (3 articles, 238 total link strength, 200 citations) indicate the formation of distinct epistemic communities around RI discourse (Table 2). The strong presence of *NanoEthics* (10 articles) and the emergence of domain specific journals like *NanoImpact* reflect the field's evolution toward specialized sub disciplines. However, the relatively limited presence of broader interdisciplinary journals suggests that RI in nanotechnology may be developing in relative isolation from mainstream innovation studies, policy research, and sustainability science. This pattern raises questions about the integration of RI perspectives into broader academic and policy discussions about technology governance and societal challenges.

Perhaps the most significant finding of this study is the notable absence of explicit connections between RI-nanotechnology research and Grand Societal Challenges. Despite our targeted search strategy combining all three domains, none of the eight identified clusters directly addresses GSCs as an organizing framework. This absence is particularly striking given the European Union's emphasis on challenge oriented innovation policy through programs like Horizon 2020 and Horizon Europe, which explicitly frame research and innovation activities around societal challenges.[36,37] The lack of GSC terminology in the keyword co-occurrence analysis and its absence from the density visualization map suggest that the RI nanotechnology community has not yet fully embraced challenge oriented approaches to innovation. This represents a significant missed opportunity, as nanotechnology's cross-cutting nature makes it particularly well suited to addressing complex, systemic challenges that span multiple sectors and disciplines.

Our keyword and cluster analysis also largely reflect established RRI themes. For instance, Cluster 1 (Value Sensitive Design in Advanced Nanotechnologies) emphasizes embedding values into technology, which is consistent with RRI's normative ethos. Indeed, Stilgoe *et al.* (2013) define RRI as taking care of the future through collective stewardship of science and innovation, highlighting anticipation, reflexivity, inclusion, and responsiveness (the AIRR dimensions).[6] This principle of VSD building ethical foresight into emerging tech, is also implied by Liu *et al.* (2022)[66]'s observation that RRI's theoretical focus is on "negative externalities and ethical issues of emerging technologies" like nanotech.[66] The Cluster 5 (Embedding Ethical Norms in Scientific Practice) directly embodies this: researchers must reflect on societal impacts and lead with integrity, mirroring Stilgoe *et al.* (2013)[6]'s call for anticipatory reflexivity and inclusion in science.

Cluster 2, labeled as "Collaborative Ecosystems for Emerging Technologies" emphasizes multi-actor, cross disciplinary innovation systems. This correlation is frequently acknowledged within academic literature. Liu *et al.* (2022) observe that RRI publications frequently appear across diverse fields such as engineering, biochemistry, computer science, and agriculture over time, reflecting RRI's close association with evolving technological advancements.[66] In scholarly practice, there has been advocacy for integrating innovation ecosystems with RRI principles. For instance, Foley and Wiek (2017), among others, describe nanotechnology itself as a complex ecosystem comprising universities, firms, and policymakers, sometimes employing open innovation or "ecosystem" metaphors.[67] The findings of this study, such as shared learning, co-creation, and transdisciplinary networks, resonate with this perspective, as RRI-nanotech research increasingly emphasizes adaptive collaboration to steer disruptive technologies within society.[35]

Cluster 3, Governance Mechanisms for Sustainable Innovation, highlights governance in RRI, focusing on anticipatory governance, intervention studies, and sustainability, aligning with broader literature. Liu *et al.* (2022) state RRI aims to address societal challenges for society and with society, using inclusive and anticipatory processes.[66] van Wezel *et al.* (2018)[44] illustrate this in Dutch nanotech, where RRI is implemented through risk, technology, and lifecycle assessments in policy dialogues. Our findings that sustainability and SDG language are absent from keywords mirror the literature, which emphasizes governance over framing around climate or SDGs. This gap is expected; Liu *et al.* (2022)[66] note key RRI documents focus on societal and ethical aspects without addressing specific grand challenges, indicating a genuine field gap.

Cluster 4, Managing Risks through Scientific Assessment, emphasizes rigorous risk and impact analysis of nanomaterials.

This strongly aligns with precedent. van Wezel *et al.* (2018) explicitly describe "RATA" (Risk Analysis & Technology Assessment) as central to putting RRI into practice in nanotech.[44] They argue that traditional chemical risk assessment (toxicity, exposure, *etc.*) should be coupled with broader technology assessment (stakeholder dialogue, futures thinking) to address nanorisks holistically.[44] This mirrors our cluster: the literature likewise stresses early identification of unintended consequences and structured TA methods.

Cluster 5 emphasizes intrinsic values such as ethics, reflexivity, and leadership. This emphasis aligns entirely with the scholarship of RRI. We have previously referenced Stilgoe's definition (AIRR) as a normative framework.[66] Similarly, van Wezel *et al.* highlight that RRI necessitates researchers to contemplate ethical and societal dimensions alongside technical design.[44] They further conceptualize innovation as an interactive process with society, aimed at ensuring ethical acceptability and sustainability. Our finding, that ethical leadership and scientist reflexivity are fundamental components of RI, corresponds precisely with the predictions of this body of literature.

Cluster 6 covering sectors like food, agriculture, and medicine, highlights the need for targeted regulation and stakeholder engagement. Findings align with domain studies. Merck *et al.* (2022)[54] explore nano-food and agriculture, noting regulation is seen as both a barrier and a driver of innovation. They conclude well-designed frameworks can foster responsible nano-agri innovation, underscoring governance and multi-stakeholder involvement in sensitive areas.[21] Liu *et al.* (2022)[66] also link agriculture to societal needs through RRI. Overall, nano-agrifood ethics support our emphasis on co-developed regulation and public trust.

Cluster 7, Socio-Technical Integration for Innovation Justice, highlights interdisciplinarity and justice. While less explicitly documented in our reference list, it accords with calls for transdisciplinary RRI. Addressing complex tech-soc issues requires moving beyond single-discipline silos. Our cluster reflects those appeals: bringing together natural scientists, social scientists, and publics to align nanotech with social justice.[50] The RATA approach itself is an example combining toxicology with stakeholder input.

Cluster 8, Public Participation in Nanotechnology Futures, is strongly supported. Public engagement is vital in RRI: Liu *et al.* (2022)[66] note frequent social science and ethics involvement, with theories like PUS and citizen science in practice. van Wezel *et al.* (2017)[44] describe technology assessment as participatory, including public perception and stakeholders' views, fostering dialogue and trust, rooted in social sciences. Our finding on public engagement aligns with these insights. Pandey (2024)[65] emphasizes that meaningful RRI in non-Western contexts involves hearing neglected voices, advocating for a care-based RRI attentive to marginalized concerns.

While explicit GSC framing is absent, the prominence of sustainability-related terms in Cluster 3 suggests an implicit recognition of broader societal concerns. However, the treatment of sustainability appears to be primarily focused on environmental considerations rather than the broader economic, social, and governance dimensions emphasized in GSC frameworks.[2,39] This narrow conceptualization may limit the field's ability to engage with the complex, interconnected nature of contemporary global challenges.

The eight-cluster structure reveals considerable methodological sophistication in current RI approaches to nanotechnology. Cluster 1's focus on VSD demonstrates the field's commitment to embedding ethical considerations directly into technological development processes. The integration of VSD with AI and engineered nanomaterials reflects an awareness of the convergent nature of emerging technologies and the need for holistic ethical frameworks.[58] Cluster 5's emphasis on embedding ethical norms in scientific practice indicates a mature understanding of the importance of researcher reflexivity and institutional change. The connection between ethical leadership and responsible science suggests that the field has moved beyond abstract philosophical discussions toward practical implementation strategies.

Clusters 3 and 8 are, focusing respectively on governance mechanisms and public participation, demonstrate significant advances in understanding the social dimensions of RI. The emphasis on anticipatory governance and transition management (Cluster 3) reflects sophisticated thinking about managing uncertainty and complexity in emerging technology contexts. The recognition of public engagement as a cornerstone of democratic innovation (Cluster 8) indicates a commitment to inclusive approaches that go beyond traditional expert-driven technology assessment. However, the analysis reveals potential limitations in current governance approaches. The focus on managing risks through scientific assessment (Cluster 4) may reflect a continued emphasis on technical risk assessment rather than broader approaches to uncertainty and ambiguity that characterize complex societal challenges.

Cluster 6's focus on domain-specific applications in food and agriculture and nanomedicine represents an important strength in current RI approaches.[68–70] The recognition that different application domains require tailored approaches to regulation and stakeholder engagement demonstrates contextual sensitivity.[70] However, the emphasis on regulatory compliance and safety assessment may not fully capture the transformative potential of nanotechnology to address systemic challenges within these sectors.

The absence of GSC framing in current RI-nanotechnology literature suggests a fundamental paradigm gap between challenge-oriented innovation policy and academic research practice. While policy frameworks increasingly emphasize the need for mission-oriented research that addresses specific societal challenges, academic research appears to remain organized around disciplinary boundaries and traditional technology-focused approaches.[71]

This gap has important theoretical implications. Current RI frameworks, while sophisticated in addressing ethical, governance, and participatory dimensions, may be insufficient for addressing the complex, systemic nature of grand challenges. GSCs are characterized by their interconnectedness, long-term time horizons, and requirement for transformative rather than incremental innovation.[72] Addressing such challenges may require fundamentally different approaches to innovation governance that go beyond the risk management and stakeholder engagement frameworks that currently dominate RI discourse.[73]

The cluster analysis reveals significant integration challenges within the RI-nanotechnology field. While individual clusters demonstrate sophisticated understanding of specific dimensions (ethics, governance, risk, participation), the relationships between clusters suggest limited integration across these dimensions. For example, the separation between technical risk assessment (Cluster 4) and governance mechanisms (Cluster 3) may reflect disciplinary boundaries that limit holistic approaches to RI. The concept of "boundary spanning" appears in Cluster 2 but remains underdeveloped in the broader literature. This represents a significant limitation, as addressing GSCs requires extensive boundary spanning across disciplines, sectors, and scales of analysis.

The findings suggest an urgent need for developing challenge-oriented approaches to RI in nanotechnology. This would involve several key shifts:

Mission-oriented integration: future research should explore how RI frameworks can be adapted to support mission-oriented innovation approaches that explicitly target specific societal challenges. This might involve developing new methodologies for participatory challenge definition, stakeholder engagement around systemic problems, and governance mechanisms for coordinating across multiple sectors and scales.[72,74]

Systems thinking and transformation: current RI approaches focus primarily on managing the social implications of technological development. Challenge oriented approaches require more attention to how nanotechnology can contribute to systemic transformations that address root causes of societal challenges rather than merely managing their symptoms.[65,73]

Global south perspectives: the geographic concentration of current research represents a significant limitation that must be addressed. Future research should prioritize collaboration with researchers and communities in underrepresented regions,[63] both to ensure that diverse perspectives inform RI frameworks and to address the challenges that are most pressing in these contexts.[72,75]

The cluster analysis reveals the need for greater methodological innovation in RI research. Current approaches may be insufficient for addressing the complexity and interconnectedness of grand challenges. Several directions for methodological development emerge:

Participatory challenge framing: developing methods for inclusive definition and framing of societal challenges that go beyond expert-driven approaches to incorporate diverse stakeholder perspectives, including those most directly affected by the challenges.[21,76]

Long-term impact assessment: current risk assessment approaches may be inadequate for evaluating the long-term, systemic impacts of nanotechnology applications on complex challenges.[47] New methodologies are needed that can assess transformative potential rather than merely managing negative externalities.[77]

Cross-scale governance: grand challenges operate across multiple scales from local to global. RI frameworks need to develop governance mechanisms that can coordinate across these scales while maintaining democratic legitimacy and stakeholder participation.[65]

The findings have important implications for policy makers and practitioners working at the intersection of RI and societal challenges:

Innovation policy pntegration: the gap between challenge-oriented innovation policy and RI research suggests the need for better integration between policy frameworks and academic research. This might involve developing new funding mechanisms that incentivize challenge-oriented RI research and creating institutional arrangements that facilitate collaboration between researchers and policy makers.

Capacity building in underrepresented regions: the geographic concentration of research highlights the need for systematic capacity building in underrepresented regions. This should go beyond traditional technology transfer approaches to support indigenous research capacity and locally relevant RI frameworks.

Industry engagement and translation: while current research demonstrates sophisticated understanding of RI principles, there appears to be limited engagement with industry practitioners who are responsible for implementing these principles. Future work should focus on developing practical tools and frameworks that can be implemented by industry while maintaining the normative commitments of RI approaches.

5 Emerging trends and future directions in nanotechnology and responsible innovation

The network visualization analysis offers critical insights into the thematic landscape and evolving trajectories within the field of nanotechnology, particularly in the context of RI. Based on the clustering and link strength of keywords, several emerging trends and future research directions are apparent.

First, a strong convergence between technological innovation and ethical responsibility is evident. The close association between terms such as RI, VSD, moral leadership, and governance highlights a significant shift in the field.[65] This trend suggests that future advancements in nanotechnology will not occur in isolation but will be guided by ethical frameworks, participatory processes, and long-term societal impacts. Increasingly, researchers and developers are expected to adopt proactive approaches to ensure that emerging technologies align with societal values and public interests.[78]

Secondly, the visualization points toward the integration of AI with nanotechnology, as evidenced by the proximity and connection of the term AI to engineered nanomaterials and nanotechnology.[28,65] This convergence suggests that AI will likely play a crucial role in accelerating nanomaterial discovery, optimizing nanoprocessing techniques, and enabling real-time diagnostics and decision-making in various nanotech applications, including healthcare and environmental monitoring.

Another noticeable trend is the emphasis on stakeholder and public engagement, along with socio-technical integration. These terms reflect a growing recognition of the importance of inclusive innovation processes. Future research and development activities are expected to increasingly involve diverse stakeholders, including scientists, policymakers, industry actors, and civil society, in order to co-create technologies that are socially robust and widely accepted. This also implies that methods such as public deliberation, citizen science, and participatory foresight may become integral components of nanotech governance.[79]

The application of nanotechnology in interdisciplinary and practical domains such as food and agriculture and nanomedicine is also highlighted.[51,54,76] These connections suggest future expansions in the use of nanotechnology to address grand challenges such as food security, sustainable agriculture, and precision medicine.[29] The trend toward green nanotechnology and biocompatible materials further reinforces this application-oriented direction.

Furthermore, the presence of keywords like emerging technologies, innovation ecosystem, and boundary spanning indicates the growing complexity and interconnectivity of the innovation landscape. The development of nanotechnology is increasingly situated within broader innovation ecosystems that demand cross-disciplinary collaboration, institutional cooperation, and policy support.[4,50,56,59] This trend signals a need for novel institutional frameworks that support open innovation, interdisciplinary research, and dynamic regulatory mechanisms.

The consistent clustering of terms related to governance and policy assessment, including technology assessment and responsible research and innovation, points to a future where regulatory and policy innovation becomes just as critical as scientific advancement.[4,47] Anticipatory governance models, incorporating foresight, real-time monitoring, and adaptive policymaking, are likely to become more prominent in managing the uncertainties and risks associated with emerging nanotechnologies.[80]

The close proximity of AI to engineered nanomaterials in the keyword network indicates an emergent convergence between AI and nanotechnology, a trend rich in potential but also fraught with complexity. As Guston (2014)[37] emphasizes, anticipatory governance must be adapted to address the layered uncertainties inherent in converging domains: the governance mechanisms suitable for singular technologies may be inadequate for integrated AI–nanotech systems, whose risks may be compounded and more opaque. Complementing this view, risk scholars observe that combining technologies can create "layered uncertainty," reducing transparency and increasing systemic vulnerability. This underscores the need for hybrid governance frameworks, blending foresight, transparency, adaptive regulation, and stakeholder engagement, to govern these convergent innovations effectively.

6 Conclusions

This study offers the first comprehensive conceptual review exploring the intersection of RI, Nanotechnology, and GSCs using a systematic literature review (PRISMA) and keyword co-occurrence analysis *via* VOSviewer. The research reveals that while nanotechnology is extensively discussed in relation to emerging technologies and responsible governance, there remains a notable gap in explicit scholarship directly linking it to GSCs. This underscores a pressing need for more integrative research in this critical area. Eight distinct thematic clusters were identified, highlighting emerging focal points such as VSD, ethical leadership, risk governance, stakeholder engagement, and domain specific applications in food, agriculture, and nanomedicine. These clusters illustrate a growing shift toward embedding ethical principles, anticipatory governance, and interdisciplinary collaboration into the lifecycle of technological innovation.

The findings highlight five key emerging trends in the evolving intersection of nanotechnology and RI. There is a clear ethics-technology convergence, where innovation is increasingly guided by governance, ethical foresight, and societal values. The synergy between AI and nanotechnology is accelerating advancements in diagnostics, materials, and sustainability. Inclusive innovation ecosystems are taking shape, emphasizing stakeholder participation, socio-technical integration, and co-created governance. Application oriented growth is evident, particularly in health, agriculture, and environmental sectors, with a growing focus on green and biocompatible nanotechnologies. Finally, regulatory and institutional frameworks are evolving to support adaptive, anticipatory governance in response to the rising complexity of emerging technologies.

Future studies may concentrate on the intersection of the three search terms: Responsible Innovation, Nanotechnology, and Grand Societal Challenges. The absence of the keyword "Grand Societal Challenges" in the density visualization map signifies the necessity for additional research in this area. The network visualization analysis provides essential insights into the thematic landscape and developing trends within nanotechnology, especially regarding RI. Several new patterns and prospective study paths are evident based on the clustering and link strength of keywords. There is a clear correlation between technological innovation and ethical responsibility. The strong connection among concepts like RI, VSD, ethical leadership, and governance underscores a notable transformation in the discipline. The visualization maps indicate that RI and nanotechnology are the primary focal points in the research landscape, with other transdisciplinary and ethical components enriching the broader conversation. Taken together, the eight thematic clusters we identified form a coherent framework that highlights how ethical reflection, governance mechanisms, stakeholder engagement, and socio-technical integration are already shaping responsible nanotechnology. The lack of explicit links to GSCs highlights a research gap and an opportunity: aligning these themes with priorities like sustainability, health equity, and climate resilience can guide scholarship and practice toward a mission-oriented agenda. Embedding RI in nanotechnology directly within the framework of GSCs is therefore not merely desirable but essential for ensuring that emerging technologies deliver transformative and equitable contributions to society.

Author contributions

Sanduni Dabare: writing – original draft, data interpretation. Sisitha Rajapaksha: conceptualization, VOSviewer analysis, conducting the PRISMA analysis, literature review, supervision, formal analysis, writing – original draft, writing – review & editing. Imalka Munaweera: conceptualization, supervision, writing – review & editing. All authors have approved the final version of the manuscript.

Conflicts of interest

The authors declare that there is no conflict of interest.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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