RESEARCH ARTICLE OPEN ACCESS

Stakeholder Engagement as a Design Principle: Orchestrating a Digital Platform for the Safety and Sustainability of the Nanomaterials Sector

Mario Miozza[1] | Luigi Mersico[1] | Jelena Barbir[2] | Genc Alimehmeti[1] | Angelo Paletta[1]

[1]Alma Mater Studiorum—University of Bologna, Bologna, Italy | [2]Faculty of Life Sciences, Research and Transfer Centre Sustainability & Climate Change Management (FTZ-NK), Hamburg University of Applied Sciences, Hamburg, Germany

Correspondence: Mario Miozza (mario.miozza@unibo.it)

Received: 27 October 2025 | **Revised:** 15 December 2025 | **Accepted:** 31 January 2026

Keywords: action design research | knowledge co-creation | safe and sustainable by design | stakeholder engagement | sustainability-oriented platforms

ABSTRACT

The governance of chemicals and nanomaterials presents a critical challenge, as significant uncertainties regarding safety and sustainability match their innovation potential. This creates a "knowledge-to-action" gap, hindering the practical implementation of safety and sustainability by design (SSbD) principles. While stakeholder engagement is crucial, the literature provides insufficient guidance on how to orchestrate collaboration among diverse actors—such as industry, policymakers, and citizens—who hold fragmented knowledge and divergent interests. This study addresses this gap by employing an 18-month action design research methodology to co-develop the CheMatSustain Facility, a sustainability-oriented digital platform. Through iterative cycles involving a systematic literature review, open surveys, expert focus groups, and co-design workshops with over 100 stakeholders, researchers identify core governance barriers and co-create a digital artifact to overcome them. Theoretically, this paper advances stakeholder and platform theory by providing a validated empirical model of how a sustainability-oriented digital platform can function as a knowledge exchange bridging mechanism. Additionally, this paper further operationalizes stakeholder engagement as a core design principle, detailing the orchestration mechanisms necessary to translate fragmented knowledge into co-created value. In conclusion, this study presents the CheMatSustain Facility. This co-designed digital infrastructure translates abstract SSbD principles into actionable tools for industry, evidence-based syntheses for policymakers, and accessible information for citizens, thereby fostering an ecosystem for responsible innovation.

1 | Introduction

In recent years, the safety and sustainability of chemicals and nanomaterials (CNMs) have become central issues in materials science, environmental health, and policy debates, as on the one hand, they not only offer significant innovative potential to enhance product effectiveness but also bring distinct safety and sustainability threats as "very little is known about nanoscale materials and how they affect human health and the environment" (NIEHS 2025). This ambiguity creates a high-stakes dilemma for industry, regulators, and the public. Consequently, implementing frameworks like safety and sustainability by design (SSbD) has become a policy imperative, yet its practical application remains fragmented and complex, creating a significant gap between sustainable innovation goals and real-world industrial practice (Furxhi et al. 2023). Addressing this problem requires coordinating a complex network of stakeholders; however, both practice and literature reveal significant barriers to such collaboration, particularly in the exchange and dissemination of scientific knowledge (Furxhi et al. 2023; Albats et al. 2025). This paper proposes sustainability-oriented digital platforms (SODPs) and stakeholder engagement as viable solutions to address this practice problem. However, current literature is fragmented for two main reasons. First, while stakeholder theory posits engagement as vital, its application often remains normative, viewing interactions as conflict-driven negotiations rather than opportunities for organizational co-creation (Viglia et al. 2018; McIntosh et al. 2023). Second, while SODPs have emerged as a potential solution to bridge the "structural holes" between disconnected actors, the literature provides insufficient guidance on how to design and orchestrate them effectively (Burt 2004; Burt 2018). Significant gaps remain in understanding the mechanisms required to manage the inherent initiatives of multistakeholder collaboration and, crucially, to motivate heterogeneous actors, spanning industry, policy, and civil society, to share and co-create specialized knowledge for sustainable outcomes. This paper argues that a dedicated digital facility is necessary to bridge this context-literature gap. Following action design research (ADR) guidelines (Sein et al. 2011), this paper presents the CheMatSustain Facility (CMSF), a digital platform designed not merely to host information, but to actively orchestrate the stakeholder engagement required to translate fragmented scientific data into actionable sustainable practices. This iterative approach lasted 18 months, prioritized the co-creation of the CMSF by engaging final users. Our initiatives included a systematic literature review (SLR), open surveys, and expert focus groups to define the problem landscape rigorously. This was followed by a series of iterative build-and-evaluate cycles, including a review workshop and a knowledge exchange workshop, which collectively engaged over 100 relevant stakeholders to collaboratively design, validate, and refine the platform's functionalities and engagement strategies.

The present paper reports on the co-design and evaluation phases of the CMSF, rather than a fully deployed system. The findings reflect the iterative specification of requirements, functionalities, and orchestration mechanisms that emerged through cycles of stakeholder engagement. First, we confirm a landscape of deep fragmentation, identifying seven key challenges and 10 distinct problem holders, which we clustered into three macrogroups: industry, policy, and citizenship. This diagnosis informed the design of the CMSF and its four core toolboxes (SSbD toolbox database, AI computational tool, and footprint scorecard). Subsequent evaluation workshops validated the high relevance of these tools. Stakeholders consistently prioritized the need for transparency, data reliability, and user-friendly interfaces that support active decision-making over static reports, allowing the research team to identify specific usability requirements and motivational drivers essential for platform adoption and trust. This study offers significant theoretical and practical contributions. Theoretically, we provide a detailed, empirical model of how an SODP can be designed to function as an effective "tertius iungens" (Obstfeld 2005) in a high-complexity, multistakeholder domain. We advance platform orchestration theory (e.g., Mukhopadhyay and Bouwman 2019; Isckia et al. 2020) by moving beyond if platforms can engage actors to how they do so, identifying the specific design principles (e.g., transparency and co-creation) and motivational drivers (e.g., regulatory compliance and risk mitigation) that foster dialogic engagement and sustainability outcomes (Viglia et al. 2018). Practically, we deliver the CMSF, a validated, co-designed digital infrastructure that translates abstract SSbD principles into actionable, managerial guidelines for risk assessment (RA), sustainable innovation, and transparent reporting through its toolboxes.

2 | Theoretical Background

2.1 | Digital Platforms and Stakeholder Engagement

With the growing emphasis on sustainability-focused practices, organizations are broadening their objectives beyond merely addressing customer needs to encompass the expectations of multiple stakeholders. Previous literature has shown that effective stakeholder relationship management can be a valuable source of competitive advantage (Surroca et al. 2010), contributing to organizational resilience (Choi and Wang 2009) and enabling both financial and CSR benefits (Barrena-Martínez et al. 2017). Nonetheless, most relevant research often portrays organizations as entities that make decisions to benefit stakeholders without sufficiently exploring the significance of actively engaging them (Scherer and Palazzo 2007; Viglia et al. 2018). Rooted in stakeholder theory (Freeman 2010), stakeholder engagement primarily refers to practices that meaningfully involve stakeholders in organizational activities that directly or indirectly affect them (Greenwood 2007). Prior research has demonstrated that effective stakeholder engagement can enhance creativity and innovation (Wohlgemuth et al. 2019), boost efficiency and effectiveness (Scherer and Voegtlin 2020), and foster value creation (Harrison et al. 2010; Parmar et al. 2010; Harrison and Wicks 2013). However, despite the increasing scholarly focus on stakeholder theory, stakeholder engagement is still overlooked, as it is often considered inherently conflict driven during negotiations rather than as an opportunity for organizational rethinking (e.g., Putnam et al. 2016; Freeman et al. 2019). Thus, it is crucial to investigate further how stakeholders should be engaged to promote more collaborative and impactful interactions. A recent stream of research has highlighted that stakeholder engagement processes can be facilitated through digital platforms (Viglia et al. 2018; McIntosh et al. 2023). The term "digital platform" has taken on a wide range of meanings, and no widely accepted definition of "digital platform" has been established yet (Ciulli et al. 2020; McIntosh et al. 2023). As literature has evolved, many scholars have observed that the term is now frequently overused and politically charged, leading to conceptual ambiguity and inconsistent usage (Zarra et al. 2019). In this work, we follow the definition proposed by McIntosh et al. (2023), focusing on a specific subset of digital platforms, namely, SODPs, which facilitate knowledge exchange to inspire, guide, or foster sustainable action. In this literature setting, a digital platform is defined as a plug-and-play facility that enables participants to interact and exchange valuable information that would otherwise be wasted (Parker 2016). By acting as a "tertius iungens" (Obstfeld 2005), a connector of previously unlinked groups of heterogenous actors, digital platforms foster the development of new stakeholder relationships (Bürgin 2020; Ciulli et al. 2020), the co-creation of sustainable value (Viglia et al. 2018; Xiao et al. 2020; Liu et al. 2023; Wang et al. 2023), organizational performance (Cenamor et al. 2019; Khan and

Tao 2022), and to achieve sustainable development goals (Du et al. 2022; Hellemans et al. 2022). As a result, digital platforms facilitate the integration of economic, social, and environmental priorities, helping organizations navigate sustainability trade-offs (Reuter 2022; McIntosh et al. 2023).

However, despite these benefits, the literature shows a significant gap in exploring how digital platforms orchestrate engagement and interactions among heterogeneous stakeholder groups (Albats et al. 2025), including regulators, industry, researchers, and citizens, to contribute to effective sustainability outcomes. The study of SODPs is an increasingly debated topic in the literature (Hellemans et al. 2022). On the one hand, SODPs are acknowledged for their capability to mediate between various stakeholders and facilitate access to resources, knowledge, organizations, individuals, and information, which can mobilize action for sustainability initiatives (George et al. 2021). On the other hand, SODPs can generate unexpected tensions and paradoxical effects (Ghisetti et al. 2015; Pouri and Hilty 2018; Bonina et al. 2021), as diverse stakeholders' perspectives may lead to fragmented efforts failing to succeed in sustainability initiatives (Porter and Hellsten 2014; Ferraro et al. 2015; Köhler et al. 2019). Therefore, research in designing for SOPDs requires further elaboration on the incentives that motivate stakeholders to share knowledge, resources, and experience for collective action. Hellemans et al. (2022) analyzed how to manage paradoxes and tensions arising from SODPs. However, while this study widely examined how different stakeholders share and integrate their knowledge through SODPs, it lacks elucidation on which factors stimulate fruitful interaction for sustainable action. Although predicting which stakeholders can provide specific resources or knowledge is challenging, inclusive and participatory approaches position digital platforms as ecosystems that support sustainability outcomes (Ciulli et al. 2020); therefore, SODPs design choices are critical to unlocking sustainable development. Previous literature suggests that SODPs should be designed to allow diverse stakeholders not only to exchange knowledge and information but also to engage in the problem-solving process by integrating their knowledge through interactions (Majchrzak and Malhotra 2016, 2020). Specifically, this entails a co-creation process characterized by continuous feedback exchange to enhance the effectiveness of sustainability goals. This paper proposes stakeholder engagement as a key perspective in designing for SODPs, and we will later identify how these platforms facilitate enhanced knowledge exchange.

2.2 | Digital Platforms and Knowledge Exchange

The implementation of co-creation processes among diverse stakeholders is widely recognized as a complex and challenging endeavor, particularly in contexts involving social and environmental problem-solving (Padthar and Ketkaew 2024). One of the most significant barriers to effective co-creation arises from the absence of established relationships between key stakeholders (Ciulli et al. 2020); these missing connections hinder the ability of stakeholders—such as businesses, policymakers, researchers, and civil society actors—to access and mobilize knowledge held by others (Kolk and Ciulli 2020). Without such linkages, the collaborative potential of multistakeholder initiatives remains severely constrained. This phenomenon has been analytically framed through the lens of network theory, which conceptualizes the absence of direct ties between stakeholders as "structural holes" (Burt 2004; Burt 2018). Structural holes represent gaps in a network where potential value, particularly in the form of information or knowledge, is inaccessible due to the lack of intermediation (Stewart and Hyysalo 2008; Stovel and Shaw 2012). In the context of sustainability-oriented innovation, these structural discontinuities can significantly impede the flow and integration of knowledge necessary to create value (da Silva-Jean and Kneipp 2024). Previous studies on digital platforms and sustainability-oriented initiatives highlight that SODPs have emerged as a sociotechnical infrastructure that patches these structural holes, fulfilling six brokerage functions (Ciulli et al. 2020): connecting, protecting, mobilizing, informing, integrating, and measuring. Connecting represents Broker's key role, and it is a prerequisite for fulfilling the other functions (Mersico et al. 2026). Indeed, Brokers facilitate the creation of connections between different types of stakeholders in the value chain (Kolk and Ciulli 2020), effectively building trustworthy bridges (protecting) between previously disconnected parties (Marsden and Weinstein 1982; Obstfeld 2005). This process involves identifying potential stakeholders (mobilization) and enabling their interaction to facilitate both the creation and the flow of knowledge (Hellemans et al. 2022) (informing).

Coherently, a growing body of literature is investigating the role of SODPs in facilitating knowledge exchange, particularly in relation to two critical domains: the circular economy and open innovation. In the context of the circular economy, SODPs are increasingly seen as key enablers of material value retention and waste reduction (integrating). These platforms mediate interactions among stakeholders engaged in resource recovery and reuse, including the valorization of surplus materials and underutilized assets (Sarc et al. 2019; Ciulli et al. 2020). One particularly salient development is the emergence of blockchain-enabled platforms, which enhance transparency, traceability, and accountability (measuring) across complex value chains, thereby fostering more robust interorganizational collaboration within circular economy ecosystems (França et al. 2020). In addition to improving system-level efficiencies, SODPs have also demonstrated potential to influence user behavior by supporting practices such as recycling (Kurniawan et al. 2022) and second-hand consumption—most notably within the fashion industry—thus contributing to the reduction of textile waste and promoting more circular consumption patterns (Fortuna and Diyamandoglu 2017; Parguel et al. 2017). In parallel, the research stream on open innovation explores how digital platforms enable knowledge co-creation across organizational and disciplinary boundaries. Grounded in the open innovation framework (Chesbrough 2004), this stream of research conceptualizes digital platforms as dynamic environments where diverse actors, including firms, universities, public institutions, and individuals, converge to collaboratively address complex innovation challenges (Nambisan et al. 2017). Literature highlights that these platforms act as intermediaries that match problem holders with a dispersed pool of problem solvers (Feller et al. 2012; Piazza et al. 2019), thus facilitating ongoing learning, iteration, and knowledge recombination (Zhou et al. 2025). Their ability to connect distributed competencies and integrate heterogeneous knowledge domains positions digital platforms as crucial infrastructural components in the architecture of contemporary innovation systems (Howells 2024; Wiredu et al. 2025). A key element emerging from the stream of research is the role of platform owners in the orchestration process (Mukhopadhyay and Bouwman 2019; Satwekar et al. 2022). The platform owner, who often functions as the orchestrator of the metaorganization and is responsible for structuring collaboration and coordination within the platform ecosystem (Chen et al. 2022), implements governance mechanisms that define roles, standardize protocols, and align incentives across diverse participants, thereby managing complexity and ensuring the coherence of the overall system (Kretschmer et al. 2022). Such orchestration is especially crucial in distributed environments characterized by divergent interests and variable levels of institutional capacity, where platform design must strike a balance between openness and coherence (Ciulli et al. 2020).

3 | Methodology

This section presents and justifies the study's contextual background, followed by a description of the methodological underpinnings and research design that guided the development of the CMSF.

3.1 | Study Context

This study was conducted within the framework of the European CheMatSustain project (funded under HORIZON-CL4-2023-RESILIENCE-01-21), which aims to promote the safe and sustainable deployment of CNMs. While these materials offer unique performance advantages across diverse industries, ranging from electronics to biomedicine (Hussain 2018), critical concerns regarding their adverse effects on human health and environmental systems have been raised by international bodies (Malakar et al. 2021; Furxhi et al. 2023). Consequently, ensuring the safety and sustainability of CNMs is essential for their industrial scale-up, prompting the development of regulatory tools such as the SSbD framework (Stoycheva et al. 2022; Furxhi et al. 2023). Although there is growing interest among policymakers and industry stakeholders in operationalizing SSbD (Cassee et al. 2024; Soeteman-Hernández et al. 2025), current research on CNMs remains complex and often lacks the consistency required to support universal conclusions (Furxhi et al. 2023). To address these challenges, the CheMatSustain project seeks to generate safe experimental knowledge for transfer to key stakeholders; a primary strategy to achieve this is the development of SODPs to integrate data and SSbD workflows (Viglia et al. 2018). However, given that empirical evidence highlights systemic information challenges in implementation (e.g., Cassee et al. 2024) and the need for a stronger science–policy–industry interface (Soeteman-Hernández et al. 2025), this study presents the design phases of the CMSF, an SODP specifically structured to address the above gaps.

3.2 | Research Design and Data Collection

To achieve paper's objectives, this study employs the ADR methodology (Sein et al. 2011), an approach that integrates iterative design processes with qualitative data collection methods, such as surveys, interviews, and workshops, to comprehensively address practice-inspired problems (Sein et al. 2011). Given its established utility in supporting the development of digital artifacts within organizational contexts (Satwekar et al. 2024), ADR was selected as the optimal framework to link the generation of transferable knowledge with the development of a service-oriented data platform. The research was structured into four distinct phases: (I) problem formulation, (II) building intervention, (III) reflection and learning, and (IV) SODP formalization, which align with technical and management literature to detail the sequential activities undertaken over an 18-month period. This methodological trajectory, visualized in Figure 1, culminated in the creation of the CMSF, a unique digital environment designed to deploy and facilitate knowledge exchange for the enhanced safety and sustainability of CNMs. Accordingly, the results presented in this paper correspond to the "build–intervention–evaluation" stages of ADR, with a focus on formulating

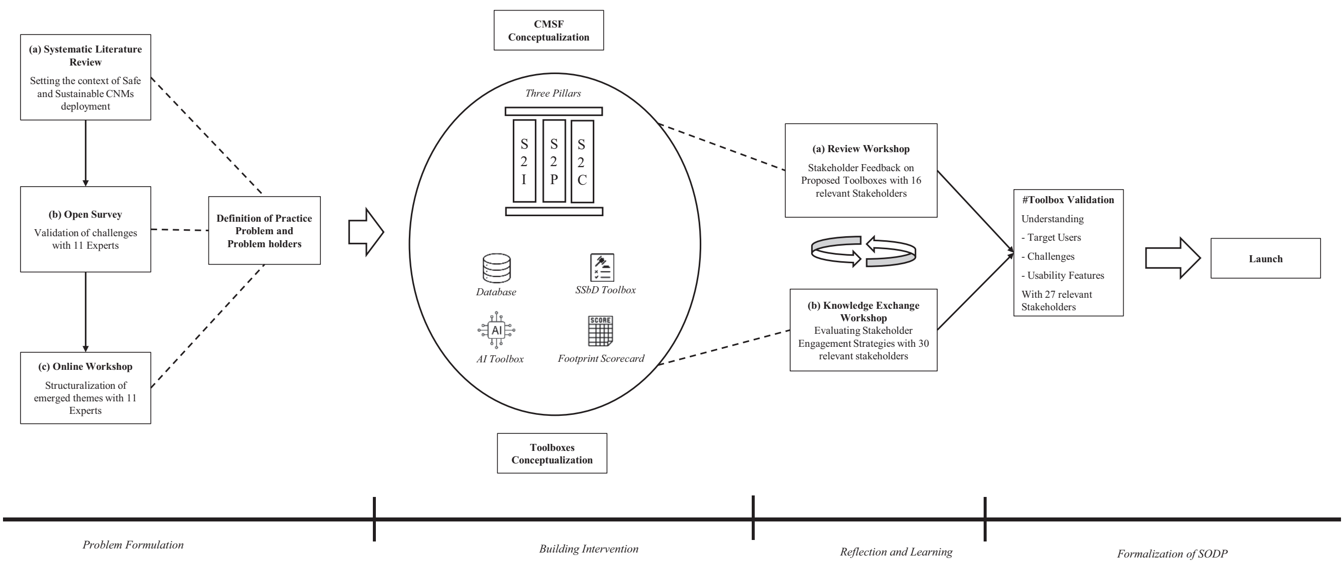

FIGURE 1 | Methodology representation.

and validating design requirements and interaction mechanisms, rather than on implementing the CMSF.

3.2.1 | Problem Formulation

The first phase integrated a detailed literature analysis with qualitative research methods to identify the practice problem and primary problem holders (Nishant et al. 2020; Auernhammer and Roth 2021). Initially, an SLR (Tranfield et al. 2003) was conducted to delineate emerging challenges regarding CNMs safety and sustainability, the findings of which were subsequently validated through an open survey administered to 11 key opinion leaders. Building on these results, the researchers organized an interactive focus group with 11 additional experts to map emerging themes to specific problem holders; the joint analysis of these three data sources provided empirical evidence for the practice problem formulation, ultimately identifying seven relevant challenges and 10 distinct problem owners.

3.2.2 | Building Intervention

Based on the findings from the initial phase, researchers determined that the most effective facilitation mechanism for bridging knowledge gaps between science and stakeholders was the design of an interactive SODP, specifically realized as the CMSF. Consequently, the second phase of the ADR methodology focused on the development and validation of digital artifacts in collaboration with problem holders to evaluate potential interventions (Sein et al. 2011). In this process, the researchers refined the categorization of problem holders into three macro-clusters—industry, policy, and citizenship at large—redefining the practice problem to align with their specific needs and challenges. This strategic alignment guided the conceptualization of the SODP, ultimately leading to the development of a Beta platform founded on three core concept pillars: Science2Policy (S2P), Science2Industry (S2I), and Science2Citizens (S2C).

3.2.3 | Evaluation, Reflection, and Learning

Following the conceptualization of the CMSF, the research team aimed at evaluating the platform's potential impact on identified stakeholders through two dedicated workshops: (a) the review workshop focused on the usability of proposed toolboxes (online) and (b) the knowledge exchange workshop designed to assess the effectiveness of engagement and knowledge transfer strategies (in person). The methodology for these sessions was deliberately structured to foster inclusive, interdisciplinary collaboration, ensuring that the codevelopment of the CMSF accurately reflected diverse perspectives from academia, industry, and policy sectors. To guarantee a balanced representation of expertise, participant profiling was conducted via interactive surveys, while experienced facilitators guided the sessions using a blend of expert presentations and interactive exercises. Stakeholder feedback was captured in real time through the Mentimeter platform—utilizing tools such as polling, word association, and prioritization tasks—yielding a total of 46 responses across the online and in-person sessions to validate the relevance and applicability of the platform's features.

3.2.4 | Formalization of SODP

To formalize the launch of the CMSF, the research team organized a final event that brought together a total of 54 participants, with 32 attending on-site and 22 attending remotely, including multiple CNMs relevant stakeholders such as academic researchers, industry representatives, policy advisors, and civil society organizations. The event pursued two main objectives. First, to formally launch the CMSF. Second, to initiate a structured dialog around the transformative potential of developed toolboxes, establishing foundations for a continuous improvement process based on stakeholder feedback.

4 | Findings

4.1 | Problem Formulation

In the initial phase of this study, the primary objective was to identify and contextualize the practice problem and the problem holder. To achieve this goal, and in accordance with the ADR framework, the researchers adopted an iterative approach, dividing activities in parallel across three main streams: (a) SLR, (b) open survey, and (c) a focus group involving key opinion experts.

4.1.1 | SLR

First, the researchers initiated an extensive SLR (Tranfield et al. 2003) aimed at identifying the main challenges emerging in the context of safe and sustainable deployment of CNMs. Following the formulation of the research question and objectives, a detailed review protocol was established to guide the selection of relevant publications. Specifically, the review adhered to a systematic selection protocol based on four criteria. Firstly, SLR involved sourcing literature from reputable academic databases—Scopus, Google Scholar, and Web of Science, using the following keywords #Chemical* #Nanomaterial* #Safe* #Sustain* #industry. An initial pool of 1667 articles was identified, from which 519 duplicates were removed. Secondly, it was restricted to peer-reviewed journal articles published in English after 2014. The year 2014 was chosen due to its significance as a turning point in linking CNMs with sustainability, prompted by the European Commission's Horizon 2020 initiative. Following a preliminary screening of titles, abstracts, and keywords, outdated papers ($n=167$), non–peer-reviewed works ($n=31$), and unpublished materials ($n=11$) were excluded. Thirdly, only those articles addressing challenges related to the safe and sustainable industrial deployment of CNMs were retained. Consequently, studies unrelated to CNMs ($n=20$) and those focused purely on scientific disciplines, such as chemistry, biology, and physics ($n=683$), were excluded. Fourthly, the SLR applied a quality assurance filter by excluding articles not published in journals listed in the ABS ranking list ($n=216$), which was considered a quality assurance base for published works in the field of management studies. The above-described criteria were strictly adhered to ensure an effective and reproducible database searching process (Tranfield et al. 2003; Sivarajah et al. 2017). As a result, we identified 20 relevant articles. Figure 2 summarizes the SLR screening process.

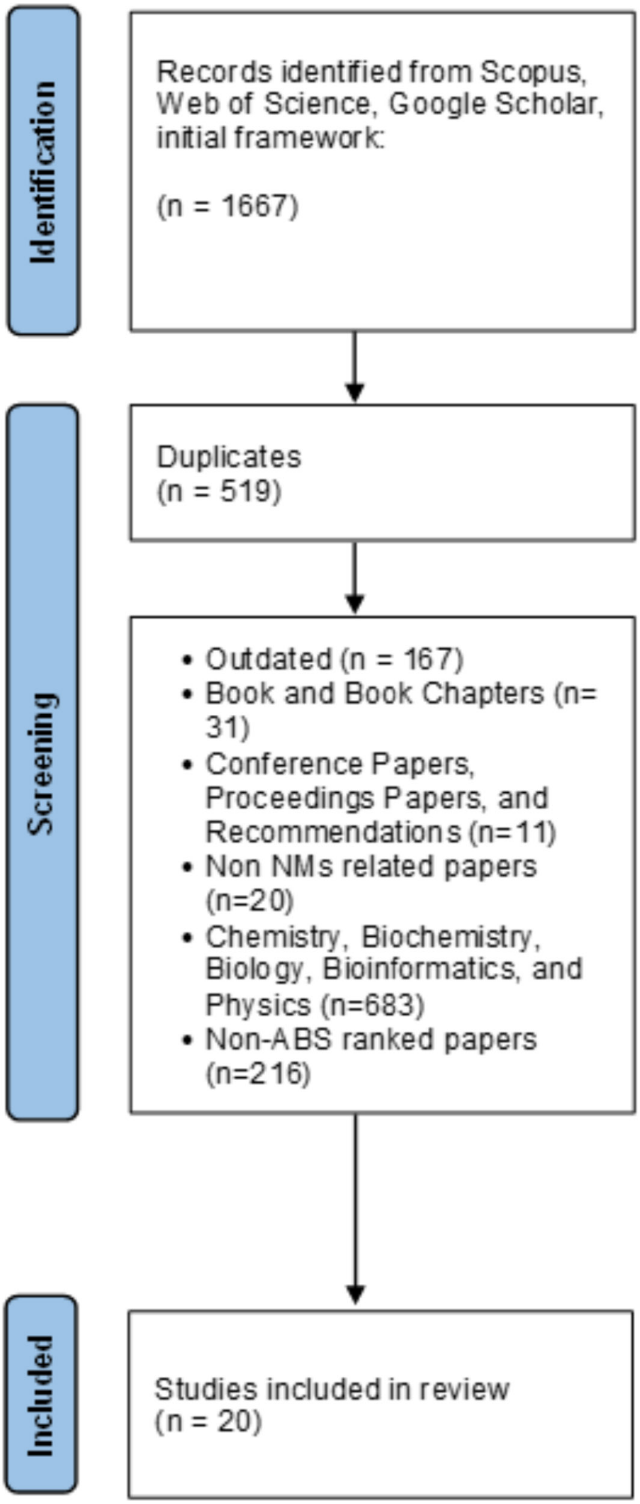

FIGURE 2 | SLR process.

In general, the SLR revealed a multifaceted and fragmented landscape of challenges associated with CNMs spanning regulatory, technical, social, and scientific dimensions. A key concern is the persistent ambiguity surrounding the definition, characterization, and life cycle assessment (LCA) of CNMs. This lack of standardization not only complicates RA processes (Justo-Hanani and Dayan 2015; Spruit 2017) but also impedes regulatory harmonization across sectors and jurisdictions (Delgado-Ramos 2014; Al-Bayati and Al-Zubaidi 2018; Basir et al. 2024). Additionally, the absence of universally accepted testing methods, coupled with a scarcity of reliable exposure data, undermines the development of robust and evidence-based risk governance frameworks (Stone et al. 2018). Furthermore, the role of private firms in knowledge production, combined with limited public sector expertise, contributes to a skewed information ecosystem and raises concerns over transparency and accountability (Karim et al. 2015; Bertoldo et al. 2016). Social challenges include widespread public unawareness of nano-related risks, insufficient consumer information, and limited worker knowledge—particularly in high-risk sectors such as construction (Arora et al. 2014; Díaz-Soler et al. 2019). Finally, the integration of sustainability considerations remains limited, with few studies addressing the intersection of CNMs and sustainable development (Cinelli et al. 2016; Nawaz et al. 2019). Overall, the findings point to an urgent need for interdisciplinary collaboration, data-driven decision-making, and proactive policy responses to ensure the safe and sustainable deployment of CNMs.

4.1.2 | Open Survey

In the following, the researchers aimed to validate the challenges identified through the SLR by developing and administering an open survey to 11 relevant experts, comprising chemists, materials scientists and engineers, LCA specialists, computational chemists, and industry representatives. The survey was designed based on literature elaboration to elicit insights from experts' domain-specific knowledge (Satwekar et al. 2024). Specifically, respondents were first asked to validate (i) the underlying rationale for promoting the safe and sustainable use of CNMs, which emerged as.

> I believe that an innovative approach to the identification of nanomaterials and chemicals, if we manage to achieve the assumed goals, will allow for quick and easy control of the presence of nanomaterials in the environment but also of degradation products of other technological products.

Furthermore, researchers sought (ii) to identify the most significant challenges in the context of CNMs. Experts shared their viewpoints on the technical, regulatory, and operational barriers that need to be addressed for safe and sustainable deployment. For instance,

- "I see the challenges mainly in how to introduce the research toxicology results into industry standard procedures for testing."
- "Semantic heterogeneous data, lack of regulations, lab-synthesized NM's may not be replicated, and hence experimental data may not be applicable to manufacturing set-up."

To conclude, experts were then asked (iii) to suggest actions or features that could enhance collaboration and communication between different stakeholders. For instance.

> (...) We need to translate the results of specialized scientific research into understandable knowledge for a wide audience.

The convergence of perspectives across phases of study underscored the urgent need for integrative frameworks that bridge scientific complexity with practical applicability.

4.1.3 | Online Focus Group

The previously obtained findings served as a foundational input for organizing an online workshop, aimed at further validating the identified practice problem with relevant stakeholders. Utilizing the Menti platform, an online focus group was conducted with 11 other relevant experts, comprising representatives from research institutions (8), industry (2), and others (1). Overall, stakeholders reported a range of barriers to the adoption of safe and sustainable CNMs. In particular, research institutions' representatives highlighted a lack of practical knowledge regarding the environmental and human health impacts of CNMs, limited expertise in LCA, and difficulties navigating complex assessment methodologies. High costs and the challenge of translating in vitro toxicity data into real-world scenarios were also seen as significant obstacles. Additionally, communication gaps and limited motivation among academic actors further impede effective technology transfer. On the industry side, participants expressed limited understanding of the specific properties of CNMs, uncertainty regarding applicable regulations, and confusion around material classification. Deficiencies in knowledge related to RA, LCA, and life cycle cost (LCC) analysis were also reported. A lack of clear benefits, inconsistent terminology, and insufficient incentives from public institutions further hinder the adoption of safe and sustainable practices. Across both academic and industrial domains, stakeholders consistently identified similar challenges: limited technical knowledge, regulatory ambiguity, and poor communication. These factors collectively contribute to the difficulty of achieving the safe and sustainable deployment of CNMs. In conclusion, the findings from the previous data collection group were consolidated, resulting in the identification of seven major challenges and the classification of 10 distinct problem holders. These outcomes provide empirical support for the definition and validation of the practice problem and problem owners, as summarized in Table 1.

4.2 | Building Intervention

Following, the research team agreed on the development of a SODP, the CMSF, designed to bridge practice problems among identified problem holders. The initial step involved conceptualizing the platform based on the empirical insights gathered in the earlier stages of the study. To this end, the researchers further refined the characterization of both the problem holders and their associated practice problems. These were then synthesized into three overarching stakeholder clusters: industry, policy, and citizens. To ensure clarity and alignment in the platform's design, the problem statement was also reformulated to reflect the specific concerns and needs of each of these three clusters. Building on this foundation, the conceptualization of the CMSF proceeded through the identification of three key components: needs covered, expected outputs, and expected outcomes. This conceptual work laid the groundwork for the subsequent design of the platform. The resulting framework is summarized in Table 2.

In general, the CMSF is built upon three fundamental pillars: S2P, S2C, and S2I. The S2P pillar aims to bridge the gap between scientific research and policymaking by engaging policymakers, regulatory bodies, and experts. It is designed to support policy decisions with research and vice versa, highlighting the growing need for the safety and sustainability of CNMs. The S2C pillar aims to engage political leaders, activists, and consumers in fostering public awareness about the safe and sustainable deployment of CNMs. By promoting informed dialog, this pillar aims to address the broader societal impacts of CNM products and create opportunities for community involvement. The CMSF brings together multiple stakeholders and is designed to enhance the practicalities of deploying CNMs across various sectors.

Based on the aforementioned challenges associated with the safe and sustainable deployment of CNMs, the research team has conceptualized four dedicated toolboxes as integral components of CMSF. These toolboxes, namely, (1) SSbD toolbox, (2) database, (3) AI computational tool, and (4) footprint scorecard, have been designed to address the multifaceted needs arising from the interaction of CNMs with regulatory, societal, and industrial domains. In particular, these toolboxes will serve as specialized instruments designed to support stakeholders in evaluating, predicting, and optimizing the sustainability and performance of CNMs across their life cycle. Each toolbox plays a distinct role, as illustrated in Table 3.

Together, these toolboxes create a comprehensive framework for guiding stakeholders in data-driven decision-making, ensuring sustainable innovation, and maintaining regulatory alignment, as evidenced in the problem formulation phase. In conclusion, based on the activities outlined above, the Beta prototype of the CMSF has been conceptualized.

4.3 | Evaluation, Reflection, and Learning

In the following, we initiated the phase aimed at evaluating, reflecting upon, and learning from the implementation of the digital artifact (Sein et al. 2011) through the organization of two additional workshops: the (a) review workshop and (b) knowledge exchange workshop. The design of these workshops was grounded in the principles of participatory research and co-creation, to foster a dialogic environment in which diverse stakeholders could critically reflect on, validate, and further refine the components of the CMSF. The (a) review workshop focused on interpreting the perceived impact of the CMSF toolboxes by relevant stakeholders, while the second (b) knowledge exchange workshop aimed to validate the effectiveness of stakeholder engagement and knowledge transfer strategies embedded within the platform itself.

4.3.1 | Review Workshop—Evaluation of Toolboxes

This online workshop engaged 16 relevant stakeholders, including (6) industry professionals, (9) researchers and scientists, and

TABLE 1 | Practice problems and problem holders.

Practice problem	Problem holder
To improve decision-making for CNM selection in the product design development and scale manufacturing operations	• Industry CNM producers • Businesses deploying CNMs • Product managers • Research and innovation managers
Establish focused working group addressing CNMs' relevant policies and regulation within the SSbD framework	• Focused academic services on sustainability, sciences, and social sciences initiatives • Industry CNM producers • Businesses deploying CNMs • Public affairs managers in regulatory compliance • National governmental agencies • Representatives from organizations at European level
To raise awareness about the uncontrolled threat to the environment and humans of CNMs	• Consumers • Citizenship at large • Industry CNM producers • Businesses deploying CNMs • Public affairs managers in regulatory compliance • National governmental agencies • Representatives from organizations at European level
Lack of communication channels between science, industry, and policymakers on CNMs	• Focused academic services on sustainability, sciences, and social sciences initiatives • Industry CNM producers • Businesses deploying CNMs • Product managers • Research and innovation managers • Public affairs managers in regulatory compliance • National governmental agencies • Representatives from organizations at European level • Consumers • Citizenship at large
Difficulty in aligning with regulatory guidelines about safety and sustainability of CNMs (when available)	• Focused academic services on sustainability, sciences, and social sciences initiatives • Industry CNM producers • Businesses deploying CNMs • Public affairs managers in regulatory compliance • National governmental agencies • Representatives from organizations at European level
To address product's life cycle reducing environmental and human impacts of CNMs	• Focused academic services on sustainability, sciences, and social sciences initiatives • Industry CNM producers • Businesses deploying CNMs • Product managers • Research and innovation managers • Public affairs managers in regulatory compliance • National governmental agencies • Representatives from organizations at European level • Consumers • Citizenship at large
Lack of knowledge and data in train and deploy AI tools to predict toxicity of CNMs	• Industry CNM producers • Businesses deploying CNMs • Product managers • Research and innovation managers

TABLE 2 | CheMatSustain Facility conceptualization.

	Science2Policy	Science2Industry	Science2Citizens
Problem statement	CNMs' deployment offers innovative solutions to many of society's current challenges, but its rapid development often outpaces regulatory frameworks due to their complexity, varying global definitions, and differing regulatory scopes. However, a greater focus on harmonizing strategies and global collaboration is still needed to ensure the safe and sustainable use of CNM-based products.	CNMs possess unique properties, making them highly valuable across industries such as electronics, biomedicine, energy, and food (etc.). However, standardized evaluations about the impacts and risks of CNMs on human health and the environment are currently lacking. Overall, this hinders the realization of their full market potential scale-up.	The application of CNMs in consumer products is steadily increasing. However, a lack of awareness and limited access to information about the risks and benefits of these materials may lead to resistance from the end users and create an information gap about CNMs on the market.
Description of target stakeholders/audience	1. *Focused academic services on sustainability, sciences, and social sciences initiatives* are local internal services in the academic institutions that can support identifying focused groups and potential stakeholders at national scale as well as facilitating the approach to initiate discussions on potential policy initiatives concerning safety and sustainability of CNMs. 2. *National governmental agencies that are involved in Nanoscience Initiatives* whose representatives can provide with information up to date concerning regulatory of CNMs at national level. 3. *EU projects* that are addressing novel CNM relevant safe and sustainability approaches. 4. *Public affairs managers in regulatory compliance* as the key element from industrial partners who are evaluating potential new regulations/policies concerning CNMs in their specific activities. 5. *Representatives from organizations at European level* that oversee the regulatory aspects involving chemicals and CNMs with the European Union.	1. *Industry CNM producers* are organizations involved in the research, manufacturing, and supply of CNMs for various applications across industries. CNM producers typically must comply with stringent regulatory frameworks governing the safety and environmental impact of CNMs, requiring them to work closely with regulatory bodies, academic institutions, and other stakeholders to ensure the responsible production and use of CNMs. 2. *Businesses deploying CNMs* are companies that integrate CNMs into their products, processes, or manufacturing systems to enhance product's performance, achieve innovative functionalities, or gain a competitive advantage in their respective industries. 3. *Product managers* are responsible for overseeing the development and commercialization of products that incorporate nanotechnology. They play a critical role in selecting materials that meet product performance, safety, and sustainability criteria. 4. *Research and innovation managers* are responsible for driving the development of novel solutions, identifying and evaluating emerging opportunities. By understanding the specific benefits of CNMs—such as enhanced strength, improved conductivity, and unique chemical reactivity—these managers can strategize the application of these materials in new products and processes.	1. *NGOs* to reach consumers of CNMs 2. *Households and consumers* to engaging in direct dialog with consumers to raise awareness of the impact of chemicals and CNMs on human health and the environment. 3. *University students* to provide them with a more in-depth scientific understanding through workshops. 4. *Schools* (teachers and pupils) to introduce key concepts in an easy way.

(Continues)

TABLE 2 | (Continued)

	Science2Policy	Science2Industry	Science2Citizens
Needs covered	• Identify key players at local, national, and European level (1, 2, and 5) • Establish an active focused working group addressing policies and regulation of CNMs within the SSbD framework (3–5) • Facilitate researchers and businesses to engage with policy-focused stakeholders, fostering open discussions and collaboration on CNM regulation and policy development. • Harmonize definitions to help progress in regulatory developments (3, 5) • Regulation about CNMs is not clear (4) • To follow up with current (CNMs) regulatory advancements (4)	• To follow up with research advancements for new applications (1–4) • To improve decision-making for material selection of new products (2–4) • To accelerate technology deployment for CNMs (e.g., computational tool to predict toxicity of CNMs) (2–4) • To address product's life cycle reducing environmental and human impacts (2–4) • To develop generally applicable models to scale CNM manufacturing (1,2,3,4) • To develop new CNM assessment methods mitigating more safe and sustainable impacts (2–4) • Lack of standard guidelines for in vitro data of particular methods (1–4) • Difficulty to scale CNM within ongoing manufacturing processes (1–4) • Harmonized nomenclature of NM (1) • Translation of in vitro toxic properties (1) • LCA and LCC data gaps (2–4)	• To grow awareness among consumers, and citizenship at large, about CNM safety and sustainability (1–4)
Expected outputs	• Focused reports including up to date EU policy initiatives along with relevant local or national activities on similar topics. • Active networking to engage in targeted thematic conferences to foster synergies with similar initiatives, allowing us to share perspectives and exchange experiences with projects aligned on regulatory objectives. • Scientific publication or report sharing perspectives on SSbD regulatory advancements for CNMs.	• Advanced computational tool development to predict the toxicity and performance of CNMs, aiding in safer and more effective material selection and deployment at large scale production level. • Digital learning resources: A robust platform for disseminating key findings, project results, and educational content, facilitating knowledge transfer and awareness-raising among stakeholders. • Impact assessment methodologies: Comprehensive tools to measure and balance economic, social, and environmental impacts, supporting sustainable decision-making and life cycle management of CNMs. • Collaborative ecosystem: A space for industry experts to share insights and drive forward the safe and sustainable use of CNMs. • Industry reports and scientific papers focusing on current challenges and opportunities of safety and sustainability of CNMs.	• Develop specific outreach and communication strategies for each audience and knowledge level. • Targeted communication materials. • Strategic NGO engagement and outreach. • School engagement and educational workshops, offering hands-on activities, case studies, and panel discussions to foster critical thinking and informed perspectives.

TABLE 3 | Toolbox conceptualization.

CMSF toolbox	Description	Bridging mechanisms within the digital platform
SSbD toolbox	Focused on sustainability and safety evaluations, this toolbox integrates risk assessment (RA) and life cycle assessment (LCA) to determine materials' environmental, social, and economic impact. It supports decision-making, ensuring that CNM deployment is aligned with planetary boundaries and sustainability goals.	Links high-level normative and regulatory frameworks with industrial practice, addressing the "LCA literacy gap" by translating abstract sustainability and safety principles into actionable design options for firms.
Database	This repository collects CNM eco-toxicity characteristics, supporting risk management, regulatory compliance, and product development, ensuring that toxicity-related human health and environmental impacts are integrated into decision-making processes.	Connects data producers and data users by standardizing currently fragmented CNM information, lowering technical barriers, and enabling regulatory as well as workflow integration.
AI computational toolbox	This tool leverages machine learning and computational models to predict CNM eco-toxicity properties, including their human health and environmental impact. It enables multidisciplinary data integration, enhances predictive accuracy, and facilitates regulatory assessments.	Mediates between advanced computational modeling and day-to-day decision-making, using interactive interfaces and explainable outputs to build trust and transparency for nontechnical users.
Footprint scorecard	This tool provides a holistic measurement framework for assessing CNMs' sustainability and safety performance. It integrates key performance indicators (KPIs) from LCA, offering insights into CNMs' economic viability, environmental footprint, and social impact. It also serves as a decision-making tool for companies looking to scale production responsibly.	Serves as a translation device, converting complex environmental and safety metrics into accessible performance scores that stakeholders can use to benchmark and inform investment, design, and policy choices.

(1) citizen groups and NGOs. Structured around a combination of presentations, interactive exercises, and collaborative discussions, participants were asked to evaluate CMSF toolboxes. This iterative, reflexive approach ensured that the insights generated were both stakeholder informed and directly actionable in the ongoing development of the CMSF. Firstly, participants were asked to collectively prioritize their issues in the CNM domain, notably the need for robust safety and sustainability assessments, more explicit regulatory guidance, and enhanced interdisciplinary expertise, and the lack of comprehensive tools capable of supporting evidence-based decisions throughout the life cycle of CNMs, which have emerged as more cogent issues. Afterwards, researchers offered stakeholders an early look at the proposed structure and functions of the CMSF toolboxes. Feedback indicated a strong interest in these components, particularly the AI tool's potential to guide safer material selection in early product development. Its capacity to reduce reliance on animal testing and accelerate innovation was viewed as promising. Secondly, the preliminary concept of the footprint scorecard was largely positive, indicating its potential relevance for practical industry applications. The evaluation of its proposed features further reinforced the appropriateness of the current development trajectory, as most functions were rated as highly significant and closely aligned in perceived importance, particularly in providing support for industry in selecting appropriate materials. Additionally, while assessing the SSbD toolbox and database functionalities, stakeholders emphasized the importance of integrating features that support regulatory compliance and risk mitigation. All proposed toolboxes were consistently ranked as highly relevant. Thirdly, the discussions further highlighted a marked prioritization of environmental and human health concerns over economic or social dimensions in RA, while evaluating the SSbD toolbox and the footprint scorecard. In conclusion, the workshop not only validated the current direction of the CMS Facility but also generated actionable feedback that will inform its continued development. By foregrounding inclusivity, co-creation, and interdisciplinarity, the event reinforced the CMSF commitment to fostering a knowledge-driven, safer, and more sustainable innovation ecosystem for CNMs.

4.3.2 | Knowledge Exchange Workshop—Evaluation of CMSF Strategies by Researchers

Following, a 45-min in-person workshop was conducted, involving 30 relevant stakeholders. Participants were first asked to identify the features that would make the CMSF both trustworthy and practically valuable. Transparency in data sources and methodological approaches emerged as key, while policy briefs and business-focused reports were deemed less relevant. A second question explored strategies to ensure ongoing engagement and mutual benefit from CMSF use. Supporting informed

TABLE 4 | Toolbox validation.

Theme	SSbD toolbox	Database	AI toolbox	Footprint scorecard
Primary end users	• Industry and private sector • Policy and regulatory stakeholders • Consumers and end users • Civil society and NGOs	• Academic scientific community • Industry and private sector • Consultants and technical experts • Policy and regulatory stakeholders • Civil society and NGOs • Tool developers and system integrators	• Academic scientific community • Industry and private sector • Consultants and technical experts • Policy and regulatory stakeholders • Civil society and NGOs • Tool developers and system integrators	• Industry and private sector • Policy and regulatory stakeholders • Consumers and end users • Civil society and NGOs
Challenges	• Standardization and harmonization of data formats • Data quality, reliability, and availability • Awareness of potential usages • Integration into development and policy • Resource constraints • Market and economic dynamics (e.g., lack of interest in sustainability) • LCA knowledge	• Data quality, reliability, and availability • Standardization and harmonization of data formats • Dissemination • Real-world application • AI model development	• Data quality, reliability, and availability • Easy to use interface • Trust and transparency of AI model • Awareness of potential usages	• Data quality, reliability, and availability • Standardization and harmonization of data formats • User engagement and understanding • Market relevance and impact
Proposed usability features	• Clarity, guidance, and training • Real-world relevance • LCA integration	• Clarity, guidance, and training • Video tutorials • Export in CSV format	• Real-world relevance and application • Creation of a BOT to support navigating the tool • Continuous improvement • Highlight database quality and integration	• Visual communication • Benchmarking • Guidance and support

decision-making in industry remained central, alongside public awareness-raising efforts that could contribute to safe and sustainable deployment of CNMs. Ultimately, participants emphasized the importance of open access, transparency, and inclusive dialog in stakeholder engagement. Recommendations included using surveys (especially consumer oriented), interviews, focus groups, and participatory meetings to gather input and foster understanding. Broad, cross-sector stakeholder dialogs were encouraged to build trust and co-create knowledge. The workshop concluded with a short plenary exchange, highlighting shared challenges and preliminary ideas for future strategic development, which will be validated in the next section activity, in line with continuous improvement principles.

4.4 | Formalization of SODP

The CMSF was officially launched through a hybrid in-person and virtual workshop, following continuous improvement practices (e.g., Shahzad and Zdravkovic 2009). A total of 54 individuals participated, with 32 attending the physical location and 22 connecting remotely. The audience represented a diverse range of relevant stakeholders, including academic experts, industry practitioners, policy professionals, representatives from civil society, and other individuals committed to promoting the safe and sustainable use of CNMs. Participant profiling was conducted via the Mentimeter platform, which enabled anonymous role identification for 27 attendees. This subset included 18 individuals affiliated with academia, seven from the industrial sector, and two representing consumer and nonprofit organizations, respectively. The core objective of this final workshop was to gather structured feedback from stakeholders to assess and improve the CMSF toolboxes. Specifically, the consultation focused on three guiding questions:

1. Who are the primary end users of each #Toolbox?
2. What are the key challenges for integrating each #Toolbox into real-world contexts?
3. What improvements would enhance the usability, value, or impact of each #Toolbox—whether in terms of user interface, guidance, or practical applicability?

The stakeholder feedback gathered from these initiatives provided valuable input for the continuous improvement of the CMSF toolboxes. A synthesis of the key findings, structured according to the three thematic questions, is presented in Table 4.

4.4.1 | Database Validation

The collected data provide a valuable snapshot of the target user landscape validated in previous phases. The identification of six primary end-user groups—including the academic scientific community, industry stakeholders, consultants, policymakers, civil society organizations, and technical developers—reflects the broad and interdisciplinary relevance of the tool across research, regulatory, and applied domains. This diverse user base underlines the necessity for a flexible and accessible design that can cater to varying levels of technical expertise and contextual needs. The challenges reported—namely, issues of data quality, availability, and reliability; the lack of standardized formats; dissemination gaps; limited real-world applicability; and complexities in AI model development—are consistent with known barriers in the deployment of digital infrastructures for CNMs that emerged in previous phases. These findings underscore the importance of establishing robust validation protocols, promoting harmonization efforts, and implementing user-oriented communication strategies to foster trust and increase uptake. In terms of usability, the emphasis on clarity, structured guidance, and training—complemented by video tutorials and exportable data formats (e.g., CSV)—suggests a strong demand for intuitive, low-threshold entry points that can support users in integrating the database into their workflows. Overall, these insights underscore the importance of co-design, transparency, and ongoing user support in ensuring the effective and sustainable deployment of such digital tools.

4.4.2 | AI Toolbox

The collected data regarding the AI toolbox offer critical insights into both its prospective user base and the key factors influencing its effective deployment. The delineation of six principal end-user groups—ranging from the academic scientific community and private sector actors to policymakers, NGOs, consultants, and technical developers—demonstrates the tool's broad applicability across knowledge production, regulatory processes, and industrial innovation. This multidimensional audience necessitates the development of adaptable, context-aware functionalities that can support diverse operational and decision-making environments. The reported deployment challenges—specifically, concerns about data quality and availability, the need for a user-friendly interface, and the imperative to build trust and transparency around AI models—mirror common barriers to the adoption of AI-driven decision-support tools in complex domains, such as CNMs. Notably, the issue of awareness of potential usages points to a broader communication and dissemination gap, highlighting the need for strategic outreach and training initiatives to foster understanding and trust among nonexpert users. The proposed usability features provide a pragmatic response to these challenges. Emphasizing real-world relevance and application aligns with the broader objective of ensuring translational value. The suggestion to implement a BOT for user guidance directly addresses the need for interactive, low-barrier access to tool functionalities. Additionally, continuous improvement and visibility into the quality and integration of underlying datasets are key enablers of long-term trust and engagement, particularly for users who require robust, transparent, and regularly updated systems. Collectively, these findings underscore the importance of user-centered design, transparency in AI processes, and iterative refinement in the successful deployment of the AI toolbox.

4.4.3 | SSbD Toolbox

The collected data concerning the SSbD toolbox highlight a precise alignment with its intended purpose of supporting decision-making across a broad spectrum of societal actors. The identified end users, including industry, regulatory stakeholders, consumers, and civil society, reflect the multilevel nature of sustainable innovation processes and underscore the toolbox's potential to act as a cross-cutting enabler of safer and more sustainable practices along the CNM value chain.

The deployment challenges reveal a complex interplay between technical, institutional, and market-related barriers. Issues related to data standardization, quality, and availability remain foundational concerns, which, if unaddressed, could undermine the consistency and comparability of assessments across sectors. Moreover, the reported lack of awareness of potential applications and difficulty in integrating the toolbox into both policy frameworks and R&D workflows suggest a need for stronger institutional anchoring and user engagement strategies. The inclusion of resource constraints and market dynamics, such as limited commercial incentives for sustainability, further highlights the structural challenges that may hinder adoption, particularly among small or resource-constrained organizations. Additionally, gaps in LCA literacy present a barrier to full exploitation of the tool's capabilities, particularly among nonexpert users. The proposed usability features, focusing on clarity, guidance, training, and real-world relevance, are well-calibrated responses to these barriers. In particular, the call for LCA integration reflects an essential step toward methodological coherence and user accessibility, especially in facilitating the interpretation of complex sustainability metrics. These findings suggest that the SSbD toolbox could significantly benefit from a stronger emphasis on user support systems, including tailored guidance materials, sector-specific examples, and enhanced communication strategies aimed at bridging the knowledge gap between scientific assessments and real-world application.

4.4.4 | Footprint Scorecard

The data collected on the footprint scorecard provides a comprehensive overview of its intended audience, key implementation challenges, and potential pathways to improve usability. The identification of diverse end users—including industry actors, policymakers, consumers, and civil society organizations—demonstrates the tool's broad relevance and underscores its potential as a multistakeholder instrument for advancing sustainability and transparency in product development and assessment. The reported challenges, particularly those related to data quality, reliability, and availability, are consistent with common barriers faced by data-driven sustainability tools. Issues about standardization and harmonization of data formats further emphasize the need for methodological coherence to ensure comparability and interoperability across sectors and applications. The inclusion of user engagement and understanding highlights the importance of fostering not only technical robustness but also accessibility and clarity for nonexpert audiences. Similarly, concerns regarding market relevance and impact underline the need to align the Scorecard's outputs with real-world decision-making contexts and value propositions, particularly in competitive business environments. To address these issues, the suggested usability features, such as visual communication, benchmarking, and guidance and support, are particularly promising. Enhancing visualization can significantly aid in the interpretation of complex metrics, making the scorecard more accessible to both technical and lay audiences. Benchmarking adds value by contextualizing performance and facilitating comparison, which is essential for market uptake. Finally, robust guidance and user support mechanisms can bridge the gap between data complexity and practical utility, encouraging broader adoption and effective integration into sustainability-oriented practices. Overall, the insights suggest that the footprint scorecard is well positioned to contribute meaningfully to sustainable decision-making, provided that efforts are made to enhance user-centric design, ensure data robustness, and establish its relevance within both regulatory and market frameworks.

4.5 | Formalizing the Bridging Mechanisms of CMSF

To formalize the bridging mechanisms, the CMSFs knowledge exchange by acting as a broker that connects diverse stakeholder groups, ranging from scientists, policymakers, industry, and civil society in four distinctive ways (see Figure 3).

First, the database operates as the infrastructural backbone of the CMSF and primarily fulfills the connecting, informing, and integrating brokerage functions. It links data producers (e.g., academic scientific communities) with data users (e.g., policymakers and industry stakeholders). Through this toolbox, the CMSF addresses the CNMs' fragmented information challenge by providing reliable, real-world data with standardized formats, allowing for integration of different data sources. Indeed, by prioritizing usability features such as structured guidance and exportable formats (e.g., CSV), the database toolboxes will lower informational barriers, thereby bridging the gap between technical expertise and practical, regulatory workflow integration.

Second, the AI toolbox serves as a mediator between computational innovation (e.g., technical developers) and operational decision-making (industry, regulators, and scientists) by informing, protecting, and mobilizing stakeholders. The CMSF addresses the inherent tension between complex AI modeling and user trust. By emphasizing “context-aware” functionalities and implementing interactive guidance systems (such as BOTs), the CMSF bridges the knowledge gap that often hinders the adoption of advanced AI for nontechnical experts. Overall, this facilitates a transition from opaque algorithms to transparent decision-support tools, ensuring that the predictive power of AI is accessible and trustworthy for stakeholders who require robust justification for their regulatory or industrial decisions.

Third, the SSbD toolbox serves as a key integrating and informing tool between normative frameworks (policy and regulatory requirements), industrial practice (firms and R&D units), and the broader interests of civil society. This component operationalizes more sustainable concepts into actionable industrial practices. Through this toolbox, the CMSF bridges the “LCA literacy gap” identified among nonexpert users by integrating LCA data with sector-specific guidance. By aligning scientific assessments with real-world commercial constraints and evidence, the CMSF ensures that the SSbD framework is not merely a theoretical aspiration but a viable practice, connecting policy ambitions with the structural realities of the CNM value chain.

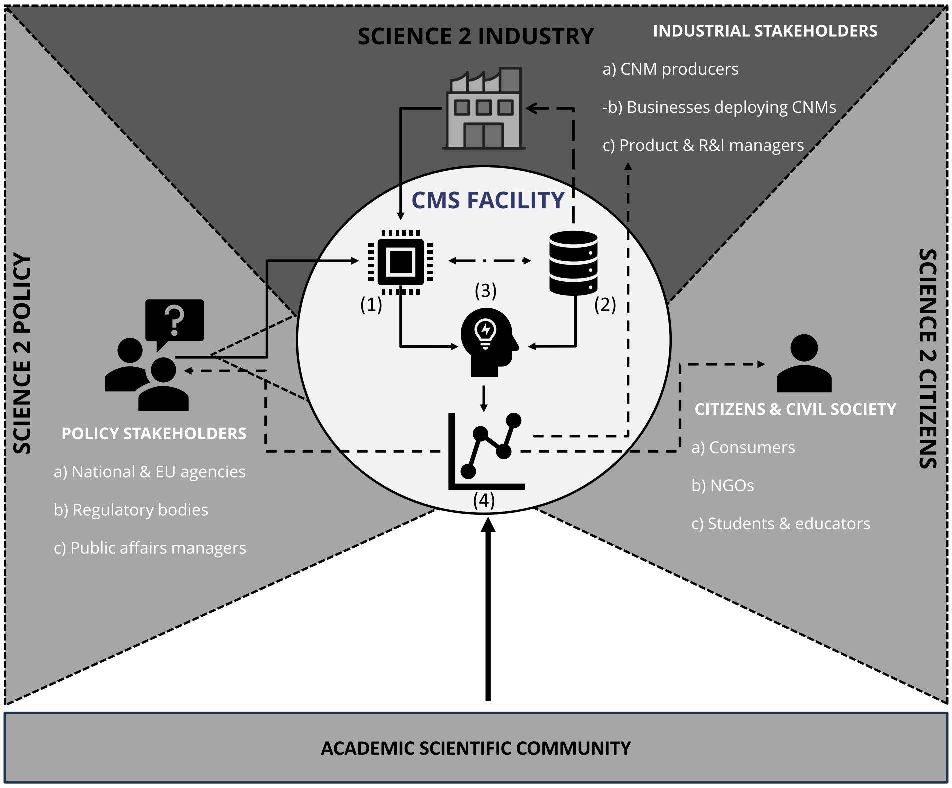

FIGURE 3 | The CMSF architecture. *Note:* (1) SSbD toolbox, (2) database, (3) AI computational tool, and (4) footprint scorecard.

Fourth, the footprint scorecard functions as a translation instrument, connecting technical safety and sustainability metrics with market and societal valuation (e.g., consumers, civil society, policymakers) (measuring and informing). This tool facilitates multistakeholder dialog by converting complex-to-quantify attributes into accessible, comparative visualizations. Through benchmarking and visual communication, the CMSF bridges the gap between abstract technical data and tangible decision-making contexts, allowing diverse stakeholders to interpret and value safety and sustainability performance, thereby aligning market competitiveness with societal demands for transparency and environmental responsibility.

In conclusion, the CMSFs knowledge exchange not merely by aggregating information and actors but by translating different stakeholder requirements into actionable insights. By establishing robust validation, enhancing usability, and fostering transparency across all four tools, the CMSF effectively bridges the divide between scientific innovation, regulatory governance, and industrial application in the CNM sector.

5 | Discussions and Theoretical Contributions

Consistent with the existing literature on stakeholder theory, which emphasizes the key role of communication, dialog, and interaction as mechanisms for effective engagement (Viglia et al. 2018), the present study illustrates that in the field of CNMs, such engagement remains constrained. This is primarily due to persistent and overlapping regulatory, technical, social, and scientific barriers (Justo-Hanani and Dayan 2015; Karim et al. 2015; Stone et al. 2018), which complicate the establishment of shared knowledge bases, weaken institutional trust, and impede stakeholder collaboration. These findings underscore the urgency of context-sensitive and interdisciplinary responses to support the safe and sustainable development in the context of CNMs (Furxhi et al. 2023). However, the study's findings highlight the potential of Stakeholder Engagement through SODP to address these barriers. Functioning as *tertius iungens* mechanisms (Obstfeld 2005; Ciulli et al. 2020), SODPs facilitate the creation of new linkages between previously disconnected actors, making them particularly suited for overcoming engagement gaps in sustainability-oriented projects that require coordinated action across academia, industry, and the public sector (de Abreu 2009). This function is particularly vital in domains such as CNM governance, where regulatory uncertainty and fragmented expertise necessitate integrated decision-making approaches. The CMSF platform developed in this study exemplifies this bridging role, demonstrating how digital infrastructures can promote stakeholder engagement by supporting multiactor dialog, enabling knowledge integration, and fostering shared value creation (Wang et al. 2023). This research further demonstrates that SODPs, when appropriately designed, can transform stakeholder engagement from a transactional process into one grounded in dialogic interaction and collective intelligence (Viglia et al. 2018; Ciulli et al. 2020; McIntosh et al. 2023). The CMSF in particular embodies this shift, as it connects disparate actors at the science–policy–industry–citizenship interface and provides tools for cross-sectoral coordination and knowledge sharing. Through mechanisms such as the AI screening toolbox and the SSbD toolbox, the platform supports not only informational exchange but also value co-creation processes. Indeed, co-creating value presupposes the existence of a broad and diverse group of actors with complementary objectives who collaborate in the co-design of innovative solutions to address societal challenges (Ciulli et al. 2020; Hellemans et al. 2022). Thus, the orchestration mechanism deployed by the platform owner represents a critical issue. Indeed, one of the most essential aspects concerns the key role of the platform owner as orchestrator. Platform owners in sustainability contexts serve not only as technical facilitators but also as metaorganizers, who are responsible for structuring the interaction space, coordinating among heterogeneous actors, and aligning stakeholder incentives (Mukhopadhyay and Bouwman 2019; Isckia et al. 2020). In line with authors (Rajala et al. 2018; Blackburn et al. 2025), the platform owner enables the creation of intelligent goods—products embedded with data, connectivity, and service logic throughout their life cycle. By defining data standards, access rights, and value-sharing rules, the platform owner ensures that the information generated within the platform flows back to industry, policymakers, and users. In doing so, the orchestrator makes it possible to design goods for durability, repair, reuse, and high-quality recovery and to align these design and policy choices with circular economy principles.

The CMSF design drew directly from this perspective, incorporating governance mechanisms to define user roles, facilitate iterative feedback, and strike a balance between system openness and structural coherence. This approach aligns with recent calls for reflexive and inclusive governance systems that can accommodate institutional diversity while maintaining a focus on shared sustainability goals (Chen et al. 2021; Kretschmer et al. 2022; Wang et al. 2023). Additionally, the review and knowledge exchange workshops revealed that stakeholders attach particular value to platform features that enhance transparency, ensure traceability of data, and guarantee open access to information. These features were consistently identified as preconditions for trust, legitimacy, and sustained stakeholder engagement, findings that align with earlier work on the social and institutional dimensions of digital platform governance (Ciulli et al. 2020; Hellemans et al. 2022). Notably, the findings not only highlight the value of traditional policy briefs or static reports but also express a preference for interactive, real-time features that support collaborative decision-making and dynamic learning. Moreover, this study contributes to the debate on value co-creation. First, it demonstrates how digital platforms, when developed through iterative, stakeholder-led design, can operationalize the principles of safe and sustainable innovation in the complex domain of CNMs. This study provides empirical validation for theoretical claims regarding the orchestration capacity of platforms, their ability to facilitate knowledge integration, and their role in enabling participatory governance. Crucially, the findings challenge technologically deterministic accounts of digital innovation (Bonina et al. 2021), instead emphasizing the importance of understanding the socio-institutional and motivational conditions that enable platforms to foster sustainable outcomes. Second, the study advances debates on stakeholder engagement and value co-creation by identifying specific motivational drivers, such as the desire to enhance regulatory compliance, mitigate environmental and health risks, and gain a competitive advantage that were surfaced in expert surveys and focus group discussions. These insights reinforce the argument that stakeholder engagement cannot be reduced to mere access to information; rather, platforms must incorporate co-creation mechanisms that are attuned to stakeholder objectives and embedded within broader institutional and market dynamics (Majchrzak and Malhotra 2016; Majchrzak and Malhotra 2020). As such, effective platform design must simultaneously address informational, technical, and relational challenges to support meaningful and sustained stakeholder participation.

6 | Managerial Implications

This research advances the theoretical and practical understanding of stakeholder engagement as a design principle for SODPs, demonstrating how this aligns diverging requirements into technical and social action. This study contributes to practice by elucidating how the CMSF and its toolboxes address critical governance, organizational, and strategic challenges in the safe and sustainable deployment of CNMs. By systematically engaging a wide range of stakeholders—spanning academia, industry, regulatory bodies, and civil society—this research generates a comprehensive understanding of the structural, procedural, and cultural barriers that hinder innovation in this emerging domain. The managerial contributions are threefold.

Firstly, the development of the CMSF database and AI computational tool responds to managerial needs for reliable, scalable, and timely data to support risk-informed decision-making. This study illustrates how relevant stakeholders perceive these disruptive tools, as well as the potential challenges and expectations associated with their more effective adoption. These tools are positioned not merely as repositories or analytical engines but as enablers of operational efficiency, knowledge integration, and strategic foresight. By offering access to harmonized datasets and predictive modeling capabilities, the tools aim to reduce information asymmetry, increase transparency, and facilitate the alignment of internal R&D practices with external regulatory and sustainability expectations. This digital infrastructure supports managers in navigating uncertainty, enhancing compliance strategies, and accelerating innovation pipelines, especially in data-poor or rapidly evolving regulatory environments.

Secondly, the SSbD toolbox represents a structured attempt to translate abstract safe and sustainability principles into actionable guidelines. This addresses how specific tools can bridge the divide between normative sustainability pressures and actual organizational processes. From a managerial perspective, this provides a platform for integrating sustainability considerations into core decision-making processes, thereby bridging the gaps between environmental, health, and economic priorities. By facilitating early-stage screening, impact forecasting, and design optimization, the toolbox supports strategic alignment between long-term sustainability goals and product development cycles. Moreover, the tool encourages proactive engagement with regulatory frameworks and investor expectations, thereby enhancing institutional legitimacy and long-term value creation.

Lastly, one of the most salient findings concerns the role of the footprint scorecard in facilitating cross-sectoral communication and stakeholder engagement. This supports in defining the mechanisms through which firms can signal substantive, rather than symbolic, commitment to human and environmental hazard, thereby legitimating their operations into sustainability action. Managers are increasingly called to respond to diverse expectations from regulators, consumers, and civil society regarding transparency and accountability in environmental performance. The footprint scorecard offers a practical mechanism for translating complex sustainability metrics into clear, digestible, and comparable outputs, thereby supporting external reporting, market differentiation, and reputational risk management. It also enables internal benchmarking and performance monitoring, reinforcing a culture of continuous improvement and responsible innovation. These managerial insights underscore the importance of co-created, user-oriented digital tools in facilitating sustainable innovation. For industry leaders and policymakers alike, the CMSF toolboxes offer operationalizable pathways for embedding sustainability into the life cycle of CNMs. They demonstrate how digital transformation—when grounded in interdisciplinary collaboration and participatory design—can generate not only technological but also organizational value. In conclusion, this paper's findings suggest that leveraging stakeholder engagement for developing SODP helps to develop a digital ecosystem, which managers can exploit to transition from reactive compliance to proactive governance, transforming the complexities of CNM sustainability into a strategic asset that enhances decision-making agility, institutional legitimacy, and long-term competitive resilience.

7 | Limitations and Future Research

While this study provides valuable scholarly and practice insights, several limitations should be acknowledged. First, the findings are primarily based on qualitative data derived from stakeholder workshops and consultations, which, although rich and contextually grounded, may reflect subjective interpretations influenced by participants' institutional backgrounds or strategic interests. To address this limitation, the research team expanded the generalizability of the results by including heterogeneous user populations. Future research could address this gap by collecting cross-sectional or longitudinal data to systematically track the evolution of stakeholders' perspectives over time. Second, the toolboxes are currently in a developmental phase, and as such, their practical effectiveness and long-term impact on organizational practices remain to be empirically validated. The perceived utility of the tools—especially the AI Computational Tool and footprint scorecard—has yet to be assessed in real-world operational settings. Despite positive feedback from relevant stakeholders, this introduces a degree of uncertainty regarding their actual uptake, integration, and performance within diverse industrial or regulatory workflows. Third, the study focuses predominantly on European stakeholders and regulatory contexts, which may limit its applicability in regions with different policy landscapes, technological infrastructures, or levels of awareness regarding CNM-related issues. This geographic concentration highlights the need for comparative studies that examine how contextual factors influence the adoption and adaptation of digital tools within global innovation ecosystems.

8 | Conclusions

While embedding SSbD principles is essential for managing the complexities of CNMs, a significant gap persists between fragmented scientific research and its practical application. The CMSF has been developed as a dedicated knowledge hub precisely to fill this gap between "what is known and what is used." Its purpose is to gather, curate, and translate scientific findings, linking exposure and hazard research directly with industrial practices, regulatory frameworks, and citizens' concerns to support evidence-informed decision-making. Overall, the CMSF (i) gathers, curates, and translates scientific findings; (ii) provides synthesis across thematics; (iii) links exposure/hazard research with industrial practices, regulatory frameworks, and citizens' concerns; and (iv) supports evidence-informed decision-making. Without such a central, well-designed facility, the fragmented nature of the scientific literature makes it difficult for nonexperts (industry decision-makers, regulators, and community stakeholders) to turn research into action.

Bridging this science–practice gap requires communication tailored to different audiences. In particular,

- For industry, the CMSF translates research into actionable insights, for example, safe-by-design guidelines, toolboxes, and exposure-mitigation strategies.
- For policymakers, the CMSF summarizes regulatory implications, highlights knowledge gaps, proposes metrics, and provides evidence to underpin governance of CNMs.
- For citizens, the CMSF explains in accessible terms what nanomaterials are, where they occur, and what is known about safety and sustainability, fostering trust, awareness, and informed public dialog.

In essence, the CMSF acts as a bridge that connects complex scientific knowledge with real-world needs, delivering clear, tailored messages to each stakeholder.

Author Contributions

Mario Miozza: conceptualization, methodology, visualization, data curation, formal analysis, investigation, writing – original draft, writing – review and editing. **Luigi Mersico:** data curation, investigation, formal analysis, writing – original draft, writing – review and editing. **Jelena Barbir:** methodology, investigation, writing – original draft, writing – review and editing. **Genc Alimehmeti:** methodology, investigation, visualization, writing – original draft, writing – review and editing. **Angelo Paletta:** conceptualization, methodology, supervision, project administration, funding acquisition, writing – original draft.

Acknowledgments

This work was supported by the HORIZON EUROPE Digital, Industry and Space under Grant No. 101137990. Open access publishing facilitated by Universita degli Studi di Bologna, as part of the Wiley - CRUI-CARE agreement.

Conflicts of Interest

The authors declare no conflicts of interest.

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