Sustainable Chemistry and Pharmacy 50 (2026) 102355

Contents lists available at ScienceDirect

Sustainable Chemistry and Pharmacy

journal homepage: www.elsevier.com/locate/scp

Safe and Sustainable by Design (SSbD) landscape: Mapping state of the art approaches along the innovation process and developing good practices☆

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A B S T R A C T

Safe and Sustainable by Design (SSbD) is a transformative approach to innovation that integrates functionality with safety, sustainability, and circularity from the earliest stages of development. By adopting a lifecycle perspective, SSbD not only minimizes risks to human health and the environment but also fosters purpose-driven innovation and strengthens industrial competitiveness. However, the practical integration of SSbD into iterative innovation processes remains a key challenge. To address this gap, this study conducted a comprehensive literature review of existing SSbD roadmaps, guidelines, and frameworks, aligning them with the early, mid, and late stages of innovation. Building on insights from the literature findings and practical examples from the packaging, textiles, automotive, energy materials, electronics, construction, and fragrance sectors, good practices were identified and structured across corporate, managerial, and operational levels. This study provides an up-to-date overview of the SSbD landscape and illustrates its implementation through good practices and value chain case examples. It demonstrates how SSbD can drive the development of safer and more sustainable chemicals, materials, products, and processes, contributing to several Sustainable Development Goals (SDGs), especially SDG3 ‘Good Health and Wellbeing’, SDG12 ′Responsible Consumption and Production’, and SDG6 ‘Clean Water and Sanitation’. As SSbD methodologies and tools continue to evolve, particularly for early-stage innovation, the approach is set to accelerate the transition toward sustainable, competitive, and resilient global markets in line with the European Union's goal for industrial competitiveness.

☆ Editor-in-Chief, Klaus Kümmerer had no involvement in the peer-review of this article and has no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to another journal editor.

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https://doi.org/10.1016/j.scp.2026.102355
Received 9 October 2025; Received in revised form 7 February 2026; Accepted 12 February 2026
Available online 24 February 2026

1. Introduction

Since the introduction of the Chemicals Strategy for Sustainability (CSS) (European Commissiona), the European landscape has changed with an added emphasis on competitiveness. The pursuit of inclusive economic growth has become a priority with the focus on the following pillars for prosperity: i) sustainable competitiveness, ii) economic security, iii) open strategic autonomy, and iv) fair competition (European Commission, 2024). The Clean Industrial Deal (European Commission, 2025), that was published in early 2025 and will synergize with the Green Deal (European Commissionb) as strategic policy orientation, outlines concrete actions to turn decarbonisation into a driver of growth for European industries. This sustainable competitiveness includes for instance lowering energy prices, creating quality jobs and the right conditions for companies to thrive.

The concept of Safe and Sustainable by Design (SSbD) started to gain attention in 2020 in the context of the European Union's (EU) efforts to promote sustainable development and reduce the environmental impact of chemicals and chemical products. The term 'Safe and Sustainable by Design' was first mentioned in the CSS (European Commissiona), introducing a new proactive measure to avoid harm to humans and the environment from chemicals, materials and products and their use. SSbD is an innovation approach that aims to integrate safety and sustainability considerations into the design of chemicals, materials, products, and processes from the very beginning of the innovation process. SSbD promotes a systemic approach to design that considers the entire lifecycle of products, from raw material extraction to end-of-life treatment. In this way, SSbD helps to design and produce chemicals, materials, and products that are safer for human health and the environment and are more sustainable by reducing the adverse impacts associated with chemical, material, and product use and identifying and designing safer alternatives. SSbD also promotes the development of more transparent and accessible information on the use and impacts of chemicals, materials, and products, enabling better decision-making and risk management. As such, SSbD plays a crucial role in achieving the EU's environmental and human health objectives, reducing waste and pollution, increasing resource efficiency, promoting the circular economy and enhancing climate change mitigation, while fostering innovation, competitiveness, and economic growth. SSbD is a necessity to support both the Green Deal (European Commissionb) and to the Clean Industrial Deal (European Commission, 2025) strategies, as it proposes criteria to evaluate safer and more sustainable solutions, including economic and social criteria in its most advanced version.

While SSbD itself is a voluntary approach, SSbD aspects are increasingly finding their way into new and upcoming regulations. On a policy level, for example, SSbD is integrated into the Ecodesign for Sustainable Products Regulation (ESPR) (Regulation, 2024/1781), which introduces a Digital Product Passport (DPP) (European Union [Internet], 2024) to achieve more environmentally sustainable and circular products. Another example is the Corporate Sustainability Reporting Directive (CSRD) (DIRECTIVE (EU) 2022/2464, 2022) under which companies have to disclose information on their Environmental, Social, and Governance (ESG) practices. SSbD helps to further deploy ESG practices by applying it to a Research & Development (R&D) projects portfolio. Applying SSbD aspects and strategies already today thereby helps industry to consolidate their safety and sustainability practices, and prepare for upcoming regulations, thereby ensuring regulatory readiness.

To bring SSbD closer to application, the European Commission' (EC) Joint Research Centre (JRC) has published a framework for SSbD chemicals and materials in 2022 (Caldeira et al., 2022), that was being revised in 2025 (Garmendia Aguirre et al., 2025). The framework integrates safety and sustainability considerations with innovation and has been complemented by a methodological guidance for SSbD (Abbate et al., 2024). In recent years, various initiatives and projects have published their approaches to bring SSbD into practice (Pizzol et al., 2023; Soeteman-Hernandez et al., 2023; European Chemical Industry Council (Cefic), 2024; Apel et al., 2024a; Abbate et al., 2025; Soeteman-Hernández et al., 2025a; Dekkers et al., 2025) and further are currently under development (Bhat et al., 2025; Serra et al., 2025).

This study aims to describe the current SSbD landscape, bring all SSbD approaches together and align them to early, mid and late innovation stages. SSbD operationalisation is further supported by state-of-the-art good practices and value chain examples.

2. Methodology

A structured literature review was conducted to identify existing guidance documents on SSbD, including roadmaps, guidance reports, and implementation approaches. Searches were performed using the keywords '*Safe-and-Sustainable-by-Design*' or '*SSbD*' in combination with '*framework*', '*guidance*', '*methodology*', '*roadmap*' or '*implementation*'. Literature searches were carried out across major scientific databases (ScienceDirect, Scopus, Web of Science, PubMed) and institutional repositories (EC, EC JRC, Organisation for Economic Co-operation and Development (OECD), European Chemicals Agency (ECHA)). In addition, a complementary Google search using the same keywords was conducted to identify relevant grey literature, such as industry reports, that is not typically indexed in scientific databases. The review covered publications from 2021 up to December 2025. Duplicate records were removed, and documents presenting identical content (e.g., a policy or project report and its corresponding peer-reviewed publication) were treated as a single entry. Working descriptions and publications addressing only individual SSbD aspects (e.g., safety or sustainability in isolation or one single end-of-life option) rather than the integrated SSbD approach were excluded. This screening process resulted in a total of thirteen SSbD guidance documents, which are described in Sections 3.1.1 to 3.1.3.

The identified SSbD guidance documents were subsequently analysed in detail. The SSbD roadmaps were examined with respect to key characteristics such as lifecycle stages addressed, links to policy and regulatory documents, and referenced databases and tools (see Supplementary Information 1). The guidance reports were analysed across a wide range of features, including design principles, assessment dimensions, trade-offs, and referenced databases and tools (see Supplementary Information 2 for the complete list of analysed features). In addition, the guidance reports and approaches were evaluated regarding their applicability at different stages of the innovation process. For simplicity, the innovation process was categorised into early innovation/business opportunity generation, mid innovation/innovation development and late innovation/innovation launch.

To complement the SSbD-focused analysis, additional literature on established sustainability approaches (i.e. methodologies and sustainability frameworks) was collected through the IRISS network (the International Ecosystem for Accelerating the Transition to Safe and Sustainable by Design materials, products and processes) (IRISS Project). Although these approaches are not explicitly developed for SSbD, they are widely used in industrial practice and often address relevant safety, environmental, social, or economic dimensions. Including them in the analysis is therefore valuable, as they can support SSbD implementation by filling methodological gaps, facilitating operationalisation in companies, enabling alignment with existing corporate practices, and fostering consistency with recognised sustainability standards and market-accepted labels. An overview and short descriptions of the analysed sustainability frameworks is presented in Section 3.1.4. The sustainability approaches were also analysed in terms of SSbD relevant aspects (see Supplementary Information 3) and early, mid, or late innovation applicability.

Based on the combined analyses, SSbD guidance documents and complementary sustainability approaches were mapped to Cooper's Stage-Gate innovation model (Section 3.2), which is widely used in industrial product development. To further support practical implementation, an inventory of databases and tools addressing safety and sustainability dimensions was compiled based on the document analysis and supplemented with targeted Google searches using tool-specific keywords (i.e. '*alternatives assessment*', '*substitution tool*', '*hazard assessment tool*', '*exposure screening*', '*screening lifecycle assessment (LCA)*', '*multi-criteria assessment*', '*portfolio sustainability assessment*'). The resulting list (see Supplementary Information 4) does not aim to be exhaustive.

The performed analyses were also served as the basis for identifying state-of-the-art good practices for the implementation of SSbD principles (Section 3.3). These practices were further enriched through the incorporation of value chain perspectives and illustrated concrete examples from each value chain (Section 3.4). Input was collected from seven value chains, including Packaging (IPC; Industrial Technical Centre for Plastics and Composites); Textiles (ETP; EU Technology Platform for the Future of Textiles & Clothing); Construction (EFCC; European Federation for Construction Chemicals); Automotive (CLEPA; European Association of Automotive Suppliers); Energy materials (IAM-I; Innovative Advanced Materials Initiative); Electronics (INL; International Iberian Nanotechnology Laboratory); and Fragrances (IFRA, International Fragrance Association).

Good practices were defined as approaches demonstrating measurable progress in at least four dimensions: i) Anticipation and early integration, whereby SSbD considerations actively shape design choices rather than being applied retrospectively; ii) Cross-disciplinary integration, evidenced by collaboration across chemistry, toxicology, materials science, engineering, and socio-economic expertise, reflecting the inherently systemic nature of SSbD; iii) Iterative learning and uncertainty management, including explicit mechanisms to address data gaps, emerging evidence, and continuous refinement rather than one-off assessments; iv) Lifecycle and systems orientation, encompassing downstream impacts, circularity, and value-chain interactions beyond intrinsic material hazards. Applying these criteria enabled the value chain examples to be analysed not merely as descriptive accounts of current practices, but as evidence of organisational capabilities and design behaviours that effectively operationalise SSbD principles. In several cases, these practices are already implemented within industry under different terminologies, highlighting their potential to support the pragmatic and effective uptake of SSbD across sectors.

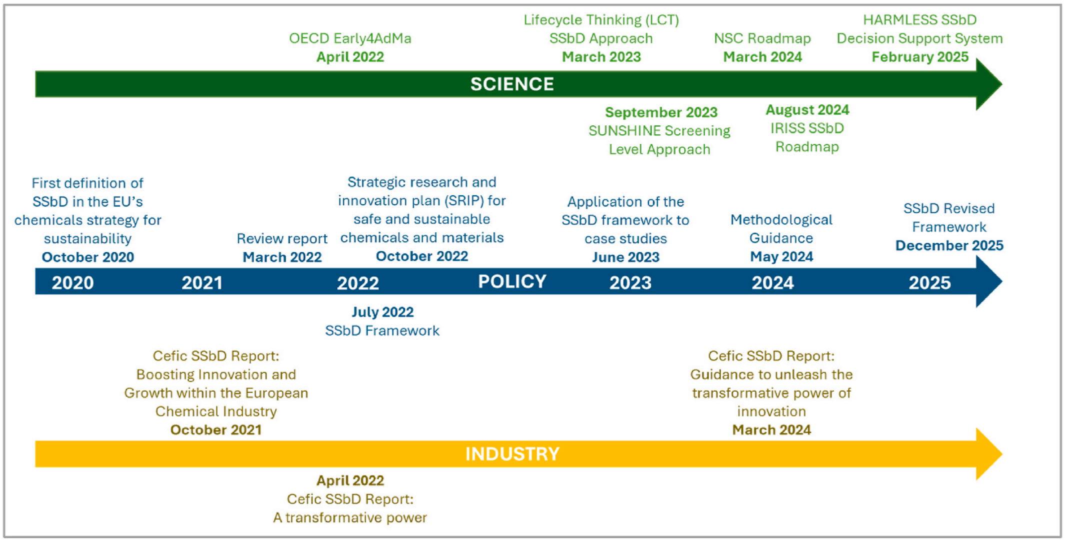

Fig. 1. Timeline highlighting key publications for the evolution of the SSbD approach.

3. Results and discussion

3.1. Current SSbD landscape: overview of guidance documents and complementary sustainability approaches

Since its initial definition in the CSS in 2020 (European Commissiona), the SSbD approach has evolved significantly over the past five years. Fig. 1 presents a timeline highlighting key publications that have shaped this development. Notably, contributions from science, policy, and industry have all played a crucial role, underscoring SSbD's function as an interface concept bridging these domains.

The following subsections 3.1.1 to 3.1.4 further describe the identified SSbD roadmaps, guidance reports, and implementation approaches, as well as other prominent sustainability approaches. Subsection 3.1.5 demonstrates how these approaches can come together to create an ecosystem for bringing SSbD into practice.

3.1.1. SSbD roadmaps

The EC published a Strategic Research and Innovation Plan (SRIP) for safe and sustainable chemicals and materials to guide research and innovation (R&I) funders in their decisions on investments and as an opportunity for a more transparent communication among all actors on joint R&I priorities (European Commission, 2022). The SRIP identified R&I needs for chemicals and materials across their lifecycle, covering (re-)design, production, use, and end-of-life. The SRIP reflects the commitment of the EC to promote industrial transformation and prosperity through R&I.

In support of the SRIP, the Network for Safety and sustainability of Chemicals and materials (NSC, former NanoSafetyCluster) has published a Roadmap for Safe and Sustainable Advanced and Innovative Materials (Cassee et al., 2024a, 2024b). This roadmap identified primary areas (issues and needs) relevant to safety and sustainability of both nanomaterials and other innovative advanced materials. It supplied directions in research to facilitate development of safe and sustainable innovative advanced materials and offered knowledge based on years of nanosafety research. In addition, it is a guidance for, amongst other, the development of the Innovative Advanced Materials for EU (IAM4EU) partnership on materials.

IRISS (IRISS Project) has published an SSbD Roadmap that identified research, education, and knowledge sharing needs and provided recommendations to support SSbD operationalisation (Apel et al., 2024b). The roadmap aimed to support the implementation of SSbD at industrial, academic, policy, and regulatory levels, by defining actions such as i) developing a common understanding of SSbD with clear definitions, terminology, and criteria and ii) developing a strategic plan and building a trusted environment to support dialogue between all SSbD stakeholders while at the same time protecting intellectual property (IP).

More detailed information on these SSbD Roadmaps can be found in the Supplementary Information 1 'Roadmaps'.

The three roadmaps differ in perspective, scope, and level of operational detail while remaining complementary. The EC SRIP takes a high-level policy and regulatory perspective with a scope covering chemicals and materials across their entire lifecycle, aiming to guide EU research and innovation funding and ensure coherence with major EU strategies and legislation. The NSC Roadmap is more technically oriented and community-driven and has a more focused scope on advanced and innovative materials. It translates years of nanosafety research into concrete research priorities and actions for advanced and innovative materials, with a particular emphasis on integrating safety into innovation processes and ensuring regulatory preparedness. The IRISS SSbD Roadmap addresses chemicals, materials, processes, and products specifically through the lens of SSbD implementation, with an emphasis on defining concrete research needs, skills and competence gaps, and knowledge-sharing actions to enable coordinated uptake of SSbD across industrial, academic, and policy contexts.

3.1.2. SSbD guidance reports

The European Chemical Industry Council (Cefic) published an assessment guidance (European Chemical Industry Council (Cefic), 2024) as the third report in an SSbD series (European Chemical Industry Council). This guidance is targeted at R&I teams within chemical companies and integrates the SSbD approach in the stage-gate innovation process by proposing five activities on how to implement SSbD at the different stages. The guidance differentiates between the design of new-to-the-world chemicals, materials, products, processes and services versus the incremental product and process re-design. To identify candidates for the re-design, the Portfolio Sustainability Assessment (PSA) methodology (World Business Council for Sustainable Development (WBCSD), 2023) can be used to analyse a company's existing portfolio of chemicals, products, processes, and services (see further information on the PSA in section 3.1.4). Furthermore, some basic rules and examples of trade-off decisions are presented.

The EC published a methodological guidance (Abbate et al., 2024) based on the feedback collected during several stakeholder consultations to clarify some aspects of the application of the JRC SSbD framework (Caldeira et al., 2022). This guidance provides explanations, examples, and suggested actions to address difficulties in implementing the steps of the safety and sustainability assessment along the innovation process. It is mainly addressed to professionals aiming to apply the JRC SSbD framework in R&I activities and to developers of funding programmes supporting such innovations. One key aspect for SSbD implementation described in the guidance is the scoping analysis that aims to define the system under study for safety and sustainability assessment. This scoping analysis builds on the system definition, the (re)design definition, and engagement with the stakeholders along the entire lifecycle. It highlights that the JRC SSbD framework goes beyond the responsibility of a single stakeholder and instead envisages the involvement and collaboration of all stakeholders along the value chain. This was recognised as one of the biggest challenges in the implementation of the first version of the SSbD framework (Caldeira et al., 2022). Together with the scoping analysis, the safety and sustainability assessments are performed in an iterative way. This iterative process allows a tiered approach starting from simplified or qualitative assessments at early stages of innovation, i.e. when the data availability is often low while uncertainties are high, followed by an intermediate or semi-quantitative assessment as data certainty and availability increase, to finalise with the full or quantitative assessments at the end of the innovation process. In this guidance, the socioeconomic assessment step (Step 5 of the JRC SSbD framework (Caldeira et al., 2022)) is seen as optional because it is not included in the EC Recommendation (European Commissionc).

The revised SSbD framework (Garmendia Aguirre et al., 2025) incorporates stakeholder feedback from the testing period of the first framework version (Caldeira et al., 2022) to enhance its support for innovation and improve its relevance, reliability, and operability. The revised SSbD framework introduces several new elements, for example, the newly defined "SSbD principles" (see Supplementary Information 2 'Guidance Reports'), which form the backbone of the framework, and a 9th SSbD design guiding principle that aims to ensure responsible sourcing and minimise social risks. The revised framework has a circular structure with emphasis on the iterative nature of its implementation throughout the innovation process. It consists of the following components: i) A scoping analysis, as introduced in the methodological guidance (Abbate et al., 2024), to contextualise the application of the framework by defining the system under study and its related (re)design objectives, ii) Selection of the SSbD scenario to tailor the following safety and sustainability assessments accordingly, iii) Safety and sustainability assessments which follow a tiered approach - simplified, intermediate, and full - enabling flexible application depending on data availability and innovation stage, iv) SSbD evaluation procedure which provides guidance on handling trade-offs and uncertainties in decision-making, and which also introduces a dashboard for visualising assessment results, and v) SSbD documentation to ensure transparency in the implementation of the framework and traceability of the results.

More detailed information on these SSbD Guidance documents can be found in the Supplementary Information 2 'Guidance Reports'.

Comparing these guidance documents show differences in perspective, scope, and level of operationalisation, yet they are highly complementary in supporting SSbD implementation along the innovation process. The revised JRC SSbD Framework primarily adopts a policy and regulatory perspective, providing a comprehensive, principles-based structure with clearly defined design principles, assessment dimensions, and minimum requirements to steer innovation towards EU Green Deal objectives while avoiding trade-offs between safety and sustainability. The JRC Methodological offers further methodological detail on how to apply safety, environmental, and socio-economic assessments iteratively across different stages of innovation. In contrast, the Cefic Guidance reflects an industry-driven perspective, embedding SSbD explicitly within stage-gate innovation processes and portfolio management, and placing stronger emphasis on functionality, business decision-making, and pragmatic handling of trade-offs under real-world constraints. While the EC JRC guidance documents ensure regulatory coherence, transparency, and consistency across sectors, the Cefic guidance enhances usability and uptake by aligning SSbD with industrial R&D workflows and decision-making practices. Together, these approaches are complementary: the JRC documents establish the normative and methodological backbone of SSbD, whereas the Cefic guidance operationalises these principles in an industrial context, facilitating effective and scalable implementation across value chains.

3.1.3. SSbD implementation approaches

3.1.3.1. Lifecycle thinking (LCT) SSbD approach. The lifecycle thinking (LCT) SSbD approach was first developed in the context of battery technologies (Soeteman-Hernandez et al., 2023). A 'big picture' analysis was performed by first identifying the biggest issues with regards to criticality, toxicity and safety, environmental and social impact, circularity, functionality, and costs in a lifecycle thinking approach. SSbD strategies are then developed using green chemistry and circular economy principles (e.g., Re-think, Re-design, Re-manufacture, Recycle, Replace, Reutilize, Recover). Finally, verification of SSbD strategies is performed via safety and sustainability assessments to ensure the SSbD strategies lead to safer and more sustainable alternatives. This approach has been recently also applied to polymeric materials in three case studies within the SURPASS (Safe-, sUstainable- and Recyclable-by design Polymeric systems - A guidance towardS next generation of plasticS) Horizon Europe project, from the building, transport, and packaging sectors (Soeteman-Hernández et al., 2025a), demonstrating its cross-sector applicability.

3.1.3.2. SUNSHINE screening level approach. The SUNSHINE (Safe and sUstainable by desigN Strategies for HIgh performance multi-component NanomatErials) Horizon 2020 project's Screening Level Approach (Pizzol et al., 2023) was developed to assist companies in integrating SSbD during the initial phases of product development, particularly focusing on multi-component nanomaterials (MCNMs). This tiered approach uses qualitative (Tier 1), semi-quantitative (Tier 2), and quantitative (Tier 3) assessment methods. Tier 1 consists of a qualitative self-assessment tool designed for early R&D stages, enabling companies to evaluate safety, sustainability (environmental, social, and economic), and functionality aspects without extensive resources. This approach considers five lifecycle stages: (1) Raw materials and resources needed to produce the material/product, (2) Production of the MCNM, (3) Production of the product incorporating the MCNM, (4) Use of the product, and (5) End-of-Life treatment. A digital platform containing tools and data is available online to support a collaborative environment for different stakeholders.[1]

3.1.3.3. HARMLESS SSbD Decision Support System. The HARMLESS (Advanced High Aspect Ratio and Multicomponent materials: towards comprehensive intelLigent tEsting and Safe by design Strategies) SSbD Decision Support System (DSS) (Dekkers et al., 2025) is a structured framework designed to assist industries in implementing SSbD during the development of advanced materials, particularly

[1] https://www.sunshine.greendecision.eu/.

focusing on complex MCNMs and high aspect ratio nanomaterials (HARNs). The DSS consists of three tools that should be used sequentially: (1) AMEA (Advanced Materials Earliest Assessment), (2) WASP (Warning Flags, design Advice, Screening Priorities), and (3) ASDI (Alternative SSbD Inspector). Each one is corresponding to specific stages of the innovation process from ideation, business case phase, and lab phase, respectively. All three tools are available online.[2]

The AMEA serves as the initial screening tool during the ideation and business case phase *(early stages of innovation)*. It consists of three straightforward questions aimed at early categorization of the material *(material categorization, DSS applicability testing, and generic design principle generation)*. Based on these responses, AMEA provides design principles and determines the applicability of the SSbD approach. AMEA offers a foundational advice to guide initial design decisions and assess potential safety and sustainability concerns, particularly distinguishing between conventional materials and advanced materials (Wohlleben et al., 2024).

The WASP is utilised after AMEA, still within the early to mid-stages of innovation (ideation and business case phase), to develop the identification of potential risks and design considerations further (Dekkers et al., 2025). With only 12 (plus three optional) questions, the user i) gains insight in which areas require specific attention, ii) gets advice on how to best change the design and iii) gets advice on what assays and guidelines to follow and which descriptors to measure in the lab phase later on.

The ASDI is employed during the laboratory phase to compare and select the most promising SSbD design variants. ASDI utilises insights from WASP to guide the measurement of specific descriptors, facilitating a comparative analysis of different design alternatives across safety, sustainability, and performance dimensions. By utilizing early warning flags identified by WASP, ASDI focuses on critical areas, streamlining the assessment process. ASDI assists innovators in making informed decisions by highlighting the strengths and weaknesses of each design variant (Dekkers et al., 2025).

3.1.3.4. OECD Early4AdMa. The Early Awareness and Action System for Advanced Materials (Early4AdMa) is a pre-regulatory risk governance tool developed by the OECD (Oomen et al., 2022; OECD, 2023). Its primary aim is to identify and describe potential safety, sustainability, and regulatory issues associated with advanced materials during their early development or use stages. This proactive approach supports regulatory readiness, enabling timely decisions to mitigate potential risks and promote responsible innovation. Although the Early4AdMa targets mainly policymakers, decision-makers, and regulators, the approach can easily be used for applying SSbD in industry. Early4AdMa consists of two tiers. Tier 1 (optional) consists of a broad screening assessment that monitors developments in advanced materials and conducts a preliminary evaluation for potential issues. This tier employs the NESSI approach (Novelty, Exposure, Severity, Scope, and Immediacy) to prioritise materials for further assessment. Tier 2 is a detailed examination of selected materials focusing on safety, sustainability, and regulatory aspects. It involves comprehensive questionnaires and expert evaluations to identify specific concerns and recommend follow-up actions.

3.1.3.5. Comparison of implementation approaches. The SSbD implementation approaches differ primarily in their level of detail, timing within the innovation process, and primary target audience, making them largely complementary rather than mutually exclusive. The LCT SSbD approach is most suitable when a holistic, system-level understanding of safety, sustainability, and circularity is required, particularly for strategic redesign efforts. This approach is explicitly tailored for early-stage innovation, though its data needs and verification steps make it adaptable to mid-stage development as well. By contrast, the SUNSHINE Screening Level Approach is designed for early R&D phases, offering a pragmatic, tiered entry point for companies, especially small and medium-sized enterprises (SMEs), to integrate SSbD considerations under conditions of high uncertainty and limited data. Its graduated structure enables progression from qualitative reflection to quantitative assessment as knowledge increases. The HARMLESS SSbD Decision Support System provides a more structured and innovation-stage-specific pathway, guiding developers of complex advanced materials from ideation through laboratory validation via sequential tools (AMEA, WASP, ASDI). It is particularly effective where targeted design feedback, prioritisation of testing, and comparison of alternatives are needed. Finally, OECD Early4AdMa operates at a pre-regulatory and governance-oriented level, focusing on early identification of potential safety, sustainability, and regulatory concerns for advanced materials. While primarily aimed at policymakers, it can complement industrial SSbD efforts by supporting anticipatory risk awareness and regulatory preparedness. Together, these approaches can be viewed as layered and reinforcing: LCT SSbD, SUNSHINE and Early4AdMa support early awareness and screening, HARMLESS enables structured design optimisation during development, and the verification step of LCT SSbD provides validation and steers innovations toward long-term safety and sustainability outcomes.

3.1.4. Prominent sustainability approaches

3.1.4.1. Portfolio sustainability assessment (PSA). The PSA is a strategic framework developed by World Business Council for Sustainable Development (WBCSD) to help companies evaluate the sustainability performance of their product and business portfolios and to align them with global sustainability goals, such as the United Nation's Sustainable Development Goals and the Paris Agreement (World Business Council for Sustainable Development (WBCSD), 2023). The purpose of the PSA is to i) guide companies in strategic decision-making regarding product development, investment, and divestment, ii) help businesses transition to more sustainable portfolios by identifying areas of risk and opportunity, and iii) foster transparency and credibility in how companies measure and report sustainability impacts. The key components of the PSA include materiality mapping, portfolio classification, impact assessment, and strategic roadmapping. In the materiality mapping, sustainability issues most relevant to the company's sector are identified, along

[2] https://diamonds.tno.nl/projects/harmlesspublic.

with the relevant stakeholders and products. In the portfolio classification, products are assessed based on impact categories (e.g., climate, water, health, circularity), classified based on categories (pioneers for products enabling sustainable solutions, transformers for products in transition, and laggards for products with misaligned sustainability impacts). In the impact assessment, metrics and indicators (e.g., carbon footprint, resource use, recyclability) are used to assess product-level sustainability performance. Finally in the strategic roadmapping, actions are developed to transform or phase out unsustainable products.

3.1.4.2. Sustainability Frameworks. Sustainability frameworks provide standardised and transparent criteria and metrics for evaluating the environmental performance of products and materials across their lifecycle. This directly aligns with the lifecycle perspective of SSbD and helps ensure that improvements in safety are not achieved at the expense of broader sustainability objectives. Moreover, sustainability frameworks are often linked to labels and certification schemes, creating strong market and innovation incentives. Positioning SSbD as a tool to gather information needed in sustainability frameworks can encourage designers, manufacturers, and developers to integrate safety and sustainability considerations early in the design phase, where interventions are typically most effective and cost-efficient.

In addition, sustainability frameworks support data generation, comparability, and communication among stakeholders. They require structured data collection and reporting, which can feed into SSbD assessments and digital tools such as DDPs. This enhances traceability, improves comparability across products and systems, and strengthens trust among regulators, industry, and consumers.

For these reasons, six prominent sustainability frameworks in the building sector were analysed in this study in terms of SSbD aspect coverage. The analysed frameworks are Byggvarubedömningen (BVB) (Byggvarubedomningen), Declare (Declare [Internet]), Environmental Data Programme (Environmental Data Program [Internet]), Home Index (Home Index [Internet], 2024), Leadership in Energy and Environmental Design (LEED) (LEED [Internet]), and SundaHus (SundaHus [Internet]). Although these frameworks were developed prior to the JRC SSbD framework, they target specific product types and already address multiple dimensions of safety and sustainability performance that are highly relevant to SSbD. More information on the analysis of these six frameworks is shown in the Supplementary Information 3.

All analysed frameworks address criteria related to the SSbD design principles and assessments proposed in the revised JRC SSbD framework (Garmendia Aguirre et al., 2025); however, the extent of coverage varies across criteria. An overview of the coverage of SSbD design principles is shown in Table 1. All frameworks cover aspects of environmental sustainability and circularity. Social sustainability is addressed only by the *Home Index* and *LEED* frameworks, and by *BVB* on a voluntary basis. Economic sustainability is not explicitly addressed by any of the frameworks analysed. Consideration of trade-offs is included only in *LEED* and *BVB*, with the latter addressing this issue by the weighting of criteria.

Overall, the analysis indicates that existing sustainability frameworks are well suited as incentives to support the applicability of SSbD, and that companies already applying them are likely to be familiar with many SSbD-related requirements. Product- and material-focused schemes such as *Declare, SundaHus* and *BVB* can reinforce the chemical safety dimension by prioritising transparency, hazardous substance phase-out, and exposure reduction across the lifecycle, directly aligning with SSbD principles on chemical safety and human health. Environmental performance–oriented frameworks such as *Environmental Data Program* and *Home Index* contribute quantitative lifecycle information, energy efficiency, carbon footprinting and circularity indicators, thereby strengthening the environmental sustainability and performance assessment aspects of SSbD. In contrast, *LEED* operates at a higher system level (entire building and its integration into the neighbourhood), integrating environmental, social and governance considerations and explicitly addressing trade-offs, which complements SSbD by contextualising product-level decisions within broader sustainability outcomes.

Table 1
Potential support of SSbD guiding design principles of sustainability frameworks. Green = Aspects related to the SSbD design principles are covered in the sustainability framework.

	Environmental data program	Home Index	Declare	LEED (v5)	SundaHus	BVB
SSbD1 *- Material efficiency*	Green	Green		Green		Green
SSbD2 *- Minimise the use of hazardous chemicals/materials*	Green		Green	Green	Green	Green
SSbD3 *- Design for energy efficiency*	Green	Green		Green		
SSbD4 *- Use renewable sources*	Green	Green		Green	Green	Green
SSbD5 *- Prevent and avoid hazardous emissions*	Green		Green	Green	Green	Green
SSbD6 *- Reduce exposure to hazardous substances*	Green		Green	Green	Green	Green
SSbD7 *- Design for end-of-life*	Green		Green	Green	Green *(only durability)*	Green
SSbD8 *- Consider the whole lifecycle*	Green	Green	Green	Green	Green	Green
SSbD9 *- Ensure responsible sourcing and minimise social risks*		Green		Green		Green *(optional)*

3.1.5. Bringing SSbD to practice through complementary approaches

Taken together, the SSbD roadmaps, guidance documents, implementation approaches, portfolio-level tools, and sustainability frameworks form a coherent and mutually reinforcing ecosystem for translating the SSbD concept into practice. Rather than representing alternative or competing approaches, these instruments operate at different levels of abstraction, stages of the innovation process (see Section 3.2), and decision-making contexts, collectively enabling the gradual and scalable operationalisation of SSbD across value chains.

At the strategic and policy level, the EC SRIP, the NSC Roadmap, and the IRISS SSbD Roadmap establish a shared long-term vision, research priorities, and enabling conditions for SSbD. They provide alignment between EU policy objectives, research and innovation funding, and emerging industrial needs, thereby creating the systemic preconditions for SSbD uptake. These roadmaps ensure coherence across chemicals, materials, and products while addressing different levels of technical depth, from high-level policy direction to community-driven research agendas and implementation-oriented capacity building.

At the methodological and procedural level, the JRC SSbD framework and its accompanying methodological guidance provide the normative backbone of SSbD implementation. They define common principles, minimum requirements, assessment dimensions, and iterative procedures that ensure consistency, transparency, and regulatory relevance. The Cefic guidance complements this by embedding SSbD into industrial stage-gate processes and portfolio management, translating principles into actionable steps that fit real-world R&D constraints and business decision-making. Together, these guidance documents bridge the gap between policy-driven expectations and industrial innovation practice.

At the operational level, SSbD implementation approaches such as the LCT SSbD approach, SUNSHINE, HARMLESS, and OECD Early4AdMa enable hands-on application of SSbD throughout the innovation lifecycle. These approaches are complementary in timing and function: Early4AdMa and SUNSHINE support early awareness, screening, and prioritisation under conditions of high uncertainty; HARMLESS provides structured decision support and targeted testing strategies during material and product development; and the LCT SSbD approach enables holistic validation and strategic redesign by embedding safety, sustainability, circularity, and functionality within a full lifecycle perspective. Used sequentially or in combination, these approaches allow SSbD to be applied in a tiered, proportionate, and resource-efficient manner.

At the portfolio and market interface, tools such as the PSA and established sustainability frameworks and labels provide a crucial link between SSbD-informed design decisions and broader business strategy, market uptake, and communication. The PSA enables companies to translate SSbD insights into portfolio-level steering, investment decisions, and transformation pathways. Sustainability frameworks and labels, in turn, operationalise many SSbD principles through concrete criteria, metrics, and disclosure requirements, supporting data generation, comparability, and traceability. By aligning SSbD with existing labels and certification schemes, companies can leverage established market incentives and reporting structures while avoiding duplication of effort.

3.2. Mapping the existing SSbD approaches to the innovation process

Innovation processes usually follow a stage-gate approach, where each gate represents a “Go/No Go” decision (Cooper, 1990; Cooper and Sommer, 2016). It can be roughly divided into early, mid, and late innovation. Based on the results presented in Section

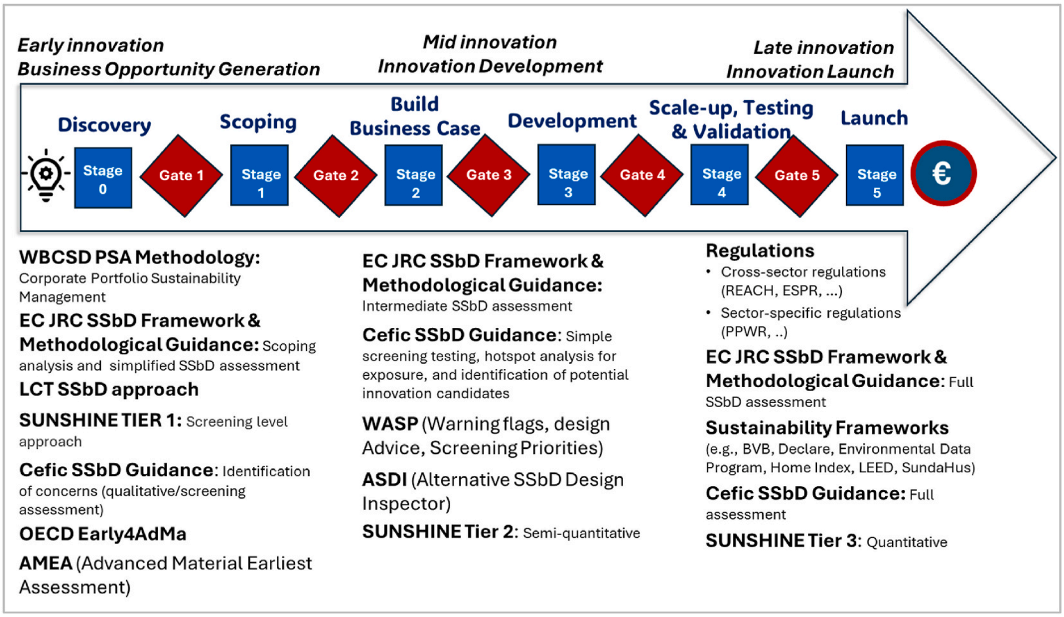

Fig. 2. Overview of SSbD approaches mapped to the different stages in the innovation process.

3.1, the following practical support can be provided on when and how to apply the existing approaches and how they can complement each other (Fig. 2).

3.2.1. *Embedding SSbD in a business case (if applicable)*

In some companies, the first step in early innovation is to start with the business case where approaches such as the *PSA* help in embedding SSbD in corporate strategies and business plans. The *PSA* can also support identifying products from the company's portfolio that do not fulfil the desired safety or sustainability criteria and should be redesigned. This can prompt chemical, material, product, or process innovation where SSbD can be applied.

3.2.2. *Early innovation (business opportunity generation)*

The early phase of the innovation process is characterised by limited data availability, a high uncertainty, and a high number of candidates and design options. Qualitative and screening type of assessments are the most suitable at this stage. Innovation managers can start by applying the *LCT SSbD approach* to identify the biggest safety and sustainability issues in their respective value chain or sector. Based on this 'big picture' analysis, innovation managers can ideally gather multi-disciplinary experts (for hazard, release and exposure, health and environmental impact, and lifecycle costing) to develop SSbD strategies that optimize functionality with safety and sustainability considerations. Alternatively, if these experts are not available (e.g., too costly for a small or medium-sized enterprise), multiple design options can be examined by small R&D teams based on corporate safe and sustainable guidance. These chemicals, materials, processes, and products can be tested by applying qualitative early screening approaches and tools. For this, a definition of the system under evaluation, including its boundaries, is first needed. Ideally, the system boundaries should reflect the whole product's lifecycle. The scoping analysis of the *JRC SSbD Methodical Guidance* can support in defining the system for (re)design, identify the stakeholders in the lifecycle, and assess and evaluate the boundaries set. This should be followed by a qualitative or simplified SSbD assessment as described in the *JRC SSbD Methodical Guidance* that can be supported by a qualitative early screening assessment as described in the *Cefic SSbD Guidance*, the *SUNSHINE Tier 1 screening level approach*, the *OECD Early4AdMa,* and the *AMEA tool*. A detailed analysis and comparison of these early innovation approaches are shown in Table 2. (Material) Safety Data Sheets, or databases/lists of substances of concern can be used to start with these qualitative questions. Additionally, *in silico* tools such as the OECD QSAR (Quantitative Structure-Activity Relationship) toolbox can be used to get more insight in the case of chemicals (Larrea-Gallegos et al., 2025). Supplementary Information 4 provides a (non-exhaustive) list of useful databases and tools.

3.2.3. *Mid-innovation (innovation development)*

In mid innovation, as more data becomes available and the number of candidates/design options is reduced, a semi-quantitative assessment can be performed with the support of the *JRC Methodological Guidance* (intermediate SSbD assessment), in complementary use with the *Cefic SSbD Guidance* (simple screening testing, hotspot analysis for exposure, and identification of potential innovation candidates). The main applicability domain of both approaches are chemicals. In case of advanced materials, the *WASP* and *ASDI tools* and/or the *SUNSHINE Tier 2* are the preferred approaches. A detailed analysis and comparison of these mid-innovation approaches are

Table 2
Comparison of early innovation approaches.

Approach	Scope	Methodology style	Data needs (early assessment)
PSA	Product & business portfolio	Indicator-based scoring & categorization; heatmap	Medium: product attributes, hazard/regulatory flags, lifecycle context
EC JRC Methodological Guidance	Chemicals/materials, associated processes, and final product/applications(s)	Tiered, criterion-based assessment (safety, environmental, circularity, socio-economic)	Medium–high: hazard, exposure, LCA info (screening data)
EC JRC revised SSbD framework	Chemicals/materials and associated processes and products	Framework/principles, no fixed scoring algorithm	Low: conceptual; used to structure assessments
LCT SSbD approach	Chemicals, products & value chains	Hotspot-oriented lifecycle thinking; streamlined LCA + hazard/exposure	Medium–high: inventory + impact proxies; can be simplified for screening
Cefic SSbD guidance	Chemicals, materials, products, processes and services	Stage-gate checklists, decision trees, qualitative scoring	Low–medium: substance profile, known hazards, use pattern, rough lifecycle picture
OECD Early4AdMa	Advanced materials (nano, complex, multi-component)	Qualitative profiling, grouping & read-across; early safety filter	Low–medium: phys-chem. properties, intended use, exposure scenarios; designed for data-poor Technology Readiness Level (TRL)
AMEA	Advanced materials/emerging applications	Tool-supported multi-criteria screening combining safety and sustainability with stage-gate-appropriateness (ideation → business case → lab phase) and also considers product, application, region combinations which is a strategic portfolio management framework	Medium: structured expert input + partial datasets; links to databases

Abbreviations: **AMEA** - Advanced Materials Earliest Assessment, **EC** – European Commission, **JRC** - Joint Research Centre, **LCA** – Lifecycle Assessment, **LCT** – Lifecycle Thinking, **OECD** - Organisation for Economic Co-operation and Development, **PSA** – Portfolio Sustainability Assessment, **TRL** – Technology Readiness Level, **WBCSD** - World Business Council for Sustainable Development.

shown in Table 3. At this innovation stage, the applicability of New Approach Methodologies (NAMs) should be considered, e.g. *in silico* and computational models such as QSAR or read across from chemical analogues, *in vitro* assays such as organ-on-chips, integrated approaches to testing and assessment (IATA), adverse outcome pathways (AOPs), and omics (see Supplementary Information 4 for useful databases and tools) (European Chemicals Agency (ECHA), 2023; RIVM, 2022).

3.2.4. Late innovation (innovation launch)

In late innovation, the focus lies on achieving compliance for retained candidates and design options. *Cross-sector* as well as *sector-specific regulations* have to be fulfilled depending on the specific innovation and new product for legal conformity and market access. *Sustainability Frameworks* can provide sector-specific guidance to ensure the innovation meets environmental and social standards and thereby support an easier entry to the market. A complementary use of these standards and SSbD can further accelerate the transition to safer and more sustainable innovations. At this innovation stage, a full and quantitative SSbD assessment needs to be performed following The *JRC SSbD Framework*, the *Cefic Guidance*, or the *SUNSHINE Tier 3* approach. Experts of some disciplines and criteria (hazard, release and exposure, health and environmental impact, and lifecycle costing specialists), as well as specific methods and tools (Supplementary Information 4), are required to perform the full and quantitative assessment. A detailed analysis and comparison of these late innovation approaches are shown in Table 4.

3.2.5. Data requirements & sources

Data availability and data quality remain among the greatest obstacles to SSbD (Guinée and Vijver, 2026). There are overlapping data requirements across all SSbD approaches, including: i) physicochemical properties; ii) hazard classifications (e.g. according to CLP (Classification, Labelling, and Packaging) or GHS (Globally Harmonized System)); iii) exposure scenarios; iv) simplified or full lifecycle inventories; v) end-of-life scenarios; and vi) use-pattern and functional performance data.

Data gaps are particularly acute in early innovation stages, where some physicochemical properties, hazard indicators, exposure scenarios, and lifecycle inventories are often missing, highly uncertain, or inferred from read-across and analogues rather than measured values. Even at later stages of development, heterogeneous data formats, inconsistent reporting practices, and limited interoperability across databases hinder effective data integration and reuse. For advanced materials and novel chemistries, these challenges are further amplified: conventional test methods may not be fully applicable, and existing databases rarely capture the complexity of multi-component systems or nano-enabled materials. Addressing these challenges requires treating data not as a passive input but as a critical infrastructure for SSbD, requiring investment in harmonized formats, shared ontologies, open repositories, and coordinated data-generation strategies. Without strengthening the data foundation, even the most advanced SSbD approaches risk being under-utilised or misapplied.

There is therefore a clear need to establish a shared SSbD data backbone that supports data generation, harmonisation, and reuse across innovation stages and assessment domains. The PARC SSbD Toolbox (see Supplementary Information 4) can contribute to addressing these challenges by providing a structured, interoperable framework that links data needs to SSbD decision-making across the innovation lifecycle. By integrating existing safety tools (e.g., CAMEO Chemicals, eChemPortal, SCIP Database), and sustainability tools (e.g., BONSAI, Ecoinvent, openLCA nexus) within a common architecture, the toolbox can help harmonise data requirements, promote consistent data formats, and improve transparency on data quality and uncertainty. In addition, the toolbox can support the use of alternative and predictive approaches—such as *in silico* methods, grouping and read-across, and tiered data strategies—to address data gaps, particularly at early innovation stages. By acting as a shared SSbD data backbone, the PARC SSbD Toolbox has the potential to reduce duplication of effort, enhance interoperability across hazard, exposure, and sustainability assessments, and

Table 3
Comparison of mid-innovation approaches.

Approach	Scope	Methodology	Data needs (mid-assessment)
EC JRC Methodological Guidance	Chemicals/materials, associated processes, and final product/applications(s)	Tiered workflow: screening → refined risk assessment + simplified LCA → socio-economic checks; documented SSbD case	Medium–high: hazard data (*in vitro*/*in silico*), exposure scenarios, simplified LCA inputs
EC JRC Revised SSbD Framework	Chemicals/materials and associated processes and products	Conceptual backbone: SSbD fundamentals, scoping, and priority criteria to guide assessments	Low (conceptual) initially; identifies essential data to collect as project matures
Cefic SSbD guidance (intermediate)	Chemicals, materials, products, processes and services	Checklist + decision trees for go/no-go; recommended targeted tests and documentation	Low–medium: substance profile, functional performance, preliminary exposure; targeted testing recommended
WASP	Advanced materials and nanomaterials (in early-to-mid TRL)	Short questionnaire → warning flags, design advice, prioritized assays; links to HARMLESS DSS	Low: 12–15 structured questions; designed for data-poor mid-assessment
ASDI	Materials & formulations (design alternatives at lab/pilot stage)	Algorithmic inspection of alternatives, suggests modifications and tests (method emerging)	Medium: requires structured design descriptors and some hazard/performance inputs.
SUNSHINE Tier-2 screening	Advanced multi-component nanomaterials and complex formulations	Screening LCA + hazard screening to identify hotspots and testing priorities	Medium: screening LCA proxies, hazard flags, use-scenario descriptors.

Abbreviations: **ASDI** - Alternative SSbD Inspector, **DSS** - Decision Support System, **LCA** – Lifecycle Assessment, **TRL** – Technology Readiness Level, **WASP** - Warning Flags, design Advice, Screening Priorities.

Table 4
Comparison of late innovation approaches.

Approaches	Scope	Methodology	Data needs (late assessment)
Regulations (e.g., REACH, ESPR, PPWR)	Varies from all chemicals, products, and/or packaging sold in the EU	Regulatory dossiers, exposure/risk assessment, labelling, DPPs	High: substance dossiers, toxicology, exposure, supply chain data
JRC Methodological Guidance	Chemicals/materials, associated processes, and final product/ applications(s)	Tiered risk assessment + simplified LCA + socio-economic checks; documented SSbD case	High: hazard data (*in vitro/in vivo/in silico*), exposure scenarios, LCA inventories
JRC Revised SSbD Framework	Chemicals/materials and associated processes and products	Framework of SSbD fundamentals, priority criteria and scoping rules	Medium: identifies essential endpoints to collect for full assessment
Cefic SSbD guidance (full assessment)	Chemicals, materials, products, processes and services	Integrated innovation workflow: technical assessment, feasibility, risk management, documentation	High: substance profiles, performance data, lifecycle and socio-economic evidence
Sustainability frameworks	Varies from materials and products to entire buildings	EPDs, material databases, substance screening, scoring systems	High: EPDs, product ingredient lists, test reports, supply-chain declarations
SUNSHINE Tier-3	Advanced multi-component nanomaterials and high-performance formulations	Screening LCA + detailed hazard/exposure integration to identify hotspots	High: detailed lifecycle inventories, advanced hazard data, use-phase and end-of-life scenarios

Abbreviations: **DPP** – Digital Product Passport, **EPD** - Environmental Product Declaration, **ESPR** - Ecodesign for Sustainable Products Regulation, **EU** – European Union, **LCA** – Lifecycle Assessment, **PPWR** - Packaging and Packaging Waste Regulation, **REACH** - Registration, Evaluation, Authorisation and Restriction of Chemicals.

facilitate more informed and timely SSbD-oriented design choices.

The EU Common Data Platform on Chemicals (European Parliament) supports the need for data availability. This platform is a new, unified digital hub managed by ECHA to centralize all chemical data (hazards, properties, uses, risks) from over 70 EU laws, making it Findable, Accessible, Interoperable, and Reusable (FAIR) by early 2029, enhancing safety, supporting sustainable chemicals, building public trust, and reducing animal testing. It creates a single “one-stop-shop” for transparent chemical risk assessment, integrating data from various agencies and establishing a framework for monitoring emerging risks and promoting safer alternatives.

3.3. *Good practices*

This section presents good practices that can support the implementation of SSbD. Such practices are essential because translating SSbD principles into real-world innovation requires more than technical tools; it also relies on coordinated organisational behaviours, skills, and governance. Good practices offer structured and transferable approaches to managing complexity, uncertainty, and data gaps while ensuring alignment between strategic intent and everyday decision-making. In doing so, they function as practical enablers for the effective, scalable, and credible implementation of SSbD across sectors and value chains.

3.3.1. *SSbD at corporate level to support a top-down approach*

Embedding SSbD at the corporate level ensures a clear top-down commitment. Integrating SSbD at this level signals that safety and sustainability are core design parameters that shape innovation from the outset, rather than being treated as project-specific or downstream considerations. This strategic anchoring enables managers across the organisation to provide the necessary governance, leadership accountability, and resources, including systematic upskilling, so that SSbD principles consistently cascade into R&D, procurement, product development, and portfolio management.

Embedding SSbD at the corporate level also reflects organisational maturity, as it requires shared understanding, cross-functional coordination, and feedback mechanisms that support continuous learning. By empowering teams to act under uncertainty, apply early screening tools, and proactively address data gaps, this approach reduces the risk of late-stage redesign and supports more anticipatory, lifecycle-aware decision-making. As such, the practice is highly transferable, offering a replicable model for other organisations to institutionalise SSbD as an organisational mindset aligned with everyday design and innovation behaviour.

3.3.2. *SSbD at management level*

Embed SSbD at the management level by leading by example: Managers at all levels and across all functions need to possess a shared, general understanding of SSbD and actively demonstrate commitment through their decisions and behaviour. Because SSbD addresses the entire product lifecycle, managers from R&D, procurement, finance, production, quality, human resources, product stewardship, and sustainability roles need to collaborate closely and contribute relevant strategies, data, and insights to SSbD assessments. When management is convinced of the benefits of SSbD for human and environmental health as well as for business performance, they are better positioned to consistently support and prioritise its implementation.

This practice strengthens an organisation's ability to translate strategic ambition into everyday decision-making. A common baseline of SSbD knowledge among managers enables coordinated, cross-functional action and turns SSbD into a shared organisational reference point rather than a specialised or siloed activity. By fostering leadership role-modelling, aligned incentives, and effective communication across departments, this approach enhances the organisation's capacity to integrate diverse evidence, manage uncertainty, and maintain coherence along the value chain. As such, it represents a highly transferable practice that illustrates how managerial engagement acts as a key lever for maturing SSbD implementation across sectors.

3.3.3. SSbD at operational level to support a bottom-up approach

Develop SSbD skills within a company, so that all necessary functions within a company have access to appropriate SSbD knowledge and skills, either internally or through external expertise. This includes roles directly involved in design and innovation, such as product developers, R&D and material engineers, as well as sustainability, social responsibility, Environmental Health & Safety (EHS), procurement, purchasing, manufacturing, and technical sales professionals. Building competence close to where design choices, material selection, and supplier interactions take place enables SSbD to be applied through everyday operational decisions rather than relying solely on specialised experts.

This practice is supported by structured and continuous learning pathways, ranging from in-house training and external courses to specialised certificate programmes or executive education for roles requiring deeper expertise. Investing in such upskilling mechanisms demonstrates organisational maturity by embedding SSbD capabilities across the workforce and sustaining them over time. Extending SSbD awareness and knowledge to customers, suppliers, and investors further reinforces this approach, recognising SSbD as a shared value-chain responsibility. By enabling knowledge diffusion across organisational boundaries, this good practice supports better data exchange, aligned expectations, and more robust decision-making under uncertainty, making it highly transferable across sectors.

Building SSbD awareness and engagement across customers, suppliers, and consumers and recognising their critical role in shaping lifecycle outcomes is essential for SSbD. This involves informing and educating external stakeholders about safe and sustainable products and practices, including material choices, appropriate use, recycling and end-of-life options, and opportunities to reduce unnecessary consumption or select more sustainable alternatives. Mapping all relevant actors along the product lifecycle and engaging them early enables a common understanding of safety and sustainability expectations, requirements, and constraints.

By extending SSbD beyond organisational boundaries, this practice demonstrates maturity in value-chain coordination and acknowledges that safety and sustainability performance depends on collective behaviour rather than isolated company decisions. Establishing structured collaboration and communication mechanisms allows stakeholders to exchange information on hazards, data needs, tools, and design assumptions, supporting more coherent decision-making under uncertainty. As a result, this practice helps align upstream design intentions with downstream use and disposal realities, reinforcing SSbD outcomes and offering a transferable model for implementation across sectors.

Foster secure information sharing and traceability along the value chain: Secure mechanisms for sharing relevant information across the value chain need to be established while safeguarding confidentiality. SSbD assessments rely on accurate and detailed data from upstream suppliers and downstream actors, yet concerns over proprietary information often restrict transparency. Implementing controlled data-sharing solutions, for instance through DPPs (European Union [Internet], 2024), and promoting high-quality data that are FAIR (Wilkinson et al., 2016; Karakoltzidis et al., 2024) enables better data flow across the product lifecycle without compromising sensitive information. This will maximize the trustworthiness and high reliability and quality of SSbD assessments (Soeteman-Hernández et al., 2024).

This practice demonstrates an organisation's ability to balance transparency with confidentiality through robust data governance. By improving traceability and ensuring controlled access to essential information, companies strengthen the reliability, consistency, and credibility of SSbD assessments. The approach is highly transferable, offering replicable models for other organisations facing similar data-sharing constraints, and illustrates how secure information-sharing frameworks function as critical enablers of effective SSbD implementation across the entire lifecycle.

Systematically identifying SSbD hotspots enables the prioritisation of high-impact lifecycle interventions across the product or process lifecycle where the most significant safety risks or sustainability gains occur. By keeping a lifecycle-wide perspective and focusing first on high-impact, “low-hanging fruit” areas, organisations can direct attention and resources to the aspects that matter most for purpose-driven innovation. This targeted approach enables innovators to structure early assessments, select relevant data, and address the most consequential issues before refining analysis in later stages.

Hotspot identification demonstrates an organisation's ability to prioritise strategically within complex systems and to manage uncertainty by concentrating on the most critical challenges. Rather than dispersing effort across marginal improvements, this practice guides design decisions through system-level insight and clear priorities. It is highly transferable, offering a replicable method that helps translate SSbD principles into concrete, actionable design choices across sectors and innovation contexts.

Establish an efficient and trustworthy science-policy-industry interface including continuous and structured collaboration between stakeholders from science and academia, policy, and industry (Soeteman-Hernández et al., 2025b). Such an interface enables the joint identification of solution needs, alignment of R&I agendas, co-development of educational materials, and the creation of SSbD-specific roadmaps that support implementation across the innovation lifecycle.

This practice demonstrates an organisation's ability to operate within a multi-actor knowledge ecosystem, aligning scientific evidence, regulatory expectations, and practical implementation challenges through trusted coordination mechanisms. Its transferability lies in the replicable governance structures it implies—such as regular dialogue platforms, joint working groups, and shared learning processes, which act as system-level enablers for coherent SSbD development across innovation, governance, and market contexts.

3.4. SSbD application in different value chains

This section presents selected examples of how SSbD is already being applied in practice today by different value chains. The examples focus on the SSbD design principles as defined in the revised SSbD framework (Garmendia Aguirre et al., 2025) – ***SSbD1***

(Material efficiency), SSbD2 (Minimise the use of hazardous chemicals/materials), SSbD3 (Design for energy efficiency), SSbD4 (Use renewable sources), SSbD5 (Prevent and avoid hazardous emissions), SSbD6 (Reduce exposure to hazardous substances), SSbD7 (Design for end-of-life), SSbD8 (Consider the whole lifecycle), and *SSbD9 (Ensure responsible sourcing and minimise social risks)* – as well as on the identified good practices (Section 3.3). The value chain examples illustrate real-world barriers and enablers of SSbD implementation, highlighting where current methods succeed or fall short.

3.4.1. Value chain examples

Packaging materials: The European packaging industry is dominated by paper and cardboard (61.6% in 2023), plastics (39.1% in 2021), and glass (62% in 2022). It comprises a mix of large companies and a high number of SMEs, with many firms employing fewer than 20 people. The packaging value chain is complex with successive converting processes and multiple stakeholders. Deployment of recycling doubles the number of stakeholders in the packaging domain. Through European rules such as the Packaging and Packaging Waste Regulation (PPWR) (Regulationa), the packaging value chain is engaged to reduce packaging waste through recycling and by incorporating recycled content in new packaging; this aligns with *SSbD7 and SSbD8*. The PPWR is very active on plastic chemicals of concern, with 980 chemicals of concern regulated under existing multilateral environmental agreements and 1021 additional plastic chemicals addressed in national and regional regulations (Wagner et al., 2024). Packaging industrials are largely impacted by these regulations and proceed for substitutions, with selection of substituting solutions that keep the same or equivalent functionalities of the packaging, in particular sanitary conditions and shelf-time of the packaging. Generally, industrials engage chemicals substitution only once regulation confirms a restriction or a ban. For the substitution, two approaches coexist: a short-term approach with substitution of banned substances only and a long-term approach with substitution of all substances of concern (*SSbD2* and *SSbD6*). The first approach can lead to regrettable substitutions that show few improvements on safety. The second approach is more innovative, durable and it brings better economic payback. Packaging facilities are focusing on reducing energy costs, carbon emissions, and waste during production, that align with *SSbD1* and *SSbD3*. This is in favour of improved sustainability, but such benefit can be lost if consumers' consumption behaviours increase used packaging tonnages.

Creating SSbD awareness and demand in the packaging sector requires making both the complexity of the value chain and the applicable regulatory requirements visible to consumers. Packaging customers might express requirements that conflict with functional performance (e.g. requesting lighter packaging that compromises product protection during transportation), making trust-building through clear, consistent communication on achieved SSbD performance essential. Awareness increases when stakeholders understand how the PPWR advances *SSbD7* and *SSbD8*, particularly through requirements on recyclability, recycled content, and restrictions on chemicals of concern. Demand can be strengthened when brands, retailers, and procurement bodies incentivise long-term substitution strategies that eliminate substances of concern (*SSbD2* and *SSbD6*) and avoid regrettable substitutions. Robust traceability systems such as transparent chemical inventories, DDPs, and verified recycled-content documentation support compliance and enable circularity. At the production level, efforts to reduce energy use, carbon emissions, and waste contribute to *SSbD1* and *SSbD3*, but these gains need to be complemented by consumer-level awareness to prevent increased packaging volumes from offsetting sustainability improvements.

Outdoor and Sports Textiles: Outdoor textiles sector faces challenges related to the use of hazardous chemicals such as per- and polyfluorinated substances (PFAS) in water-repellent coatings and the environmental impact of synthetic fibres, including microplastic pollution. Key innovations such as PFAS-free coatings, upcycled fibres, and biodegradable alternatives address these risks and contribute to *SSbD2* and *SSbD6*. Innovation in recyclability is also critical, as blended materials and durable coatings remain major barriers to textile recycling and therefore *SSbD7*.

Creating SSbD awareness and demand requires making the environmental and health impacts of material choices visible to brands, retailers, and consumers. Demand grows when procurement criteria, performance standards, and consumer expectations favour PFAS-free and circular solutions that balance functionality with intended use. Traceability tools, including transparent chemical inventories, DPPs, and verified recycling pathways, support compliance, enable *SSbD7*, and accelerate the transition toward recyclable, repairable, and circular textile systems. Improved communication can help consumers value fit-for-purpose performance, for example preferring PFAS-free water repellence suitable for everyday conditions over high-performance treatments designed for rare extreme use cases (ChemSec [Internet]).

Concrete admixtures: In the construction value chain, concrete admixtures, particularly superplasticizers, play a key role to improve the properties of concrete such as its workability, durability, or strength, while reducing CO_2 emissions and water use by up to 20% (thereby contributing to *SSbD1* and *SSbD5*). Some superplasticisers also enhance the recyclability and reuse of concrete waste (*SSbD7*). While traditional formulations often rely on hazardous raw materials such as formaldehyde- and melamine-based admixtures, newer polycarboxylate-ether (PCE) and bio-based superplasticisers use more benign and renewable raw materials. These alternatives increasingly match or improve conventional performance and support *SSbD2, SSbD4*, and *SSbD6*.

Creating SSbD awareness and demand requires highlighting the central role of admixtures in both construction performance and sustainability outcomes. Awareness increases as stakeholders recognise the risks associated with legacy formulations and the benefits of PCE-based and bio-based alternatives. Demand can be strengthened by embedding SSbD criteria into procurement practices, green-building standards, and infrastructure specifications, making safer admixtures the default choice. Enhanced traceability through DPPs under the ESPR (Regulation, 2024/1781) and the Construction Products Regulation is expected to improve transparency across the value chain (*SSbD7* and *SSbD8*), support the development of SSbD alternatives, and enable verification of gains in concrete recyclability and reuse.

End-of-Life Vehicles: The End-of-Life Vehicles Directive requires at least 80% of a vehicle's weight to be remanufactured or recycled, a target largely achieved through metal recycling. The current focus areas to further improve circularity are advanced material identification and separation at their end-of-life to enable better recycling of materials (*SSbD7*). This includes the availability of downstream data for the recycling process (data generated prior to their end-of-life). Current efforts are being made to develop i) tools for prediction of recyclates' volumes and respective material degradation/quality level, ii) strategies to maintain quality of recycled materials over multiple loops, including dedicated strategies for rare earth elements and critical materials (e.g. magnets), iii) methodologies to assess the quality of material at end-of-life (e.g., to assess the risk of certain substances preventing recycling or reuse) and to maintain it at best during use and within recycling, including to reassess the degree of quality needed, and iv) material degradation assessment methodologies based on contextual information and quality insurance criteria linked with vehicle history. Further efforts are being made to minimise the use of critical raw materials (CRM) and other critical natural resources in automotive products (*SSbD1*). This includes the development of new advanced materials to replace CRMs in critical automotive components (e.g. Ni, Co, Li, Cu, Mg, rare earth elements) while optimizing for performance, affordability, safety and sustainability. These efforts align with the EU's broader policy agenda on CRMs, including the CRM Act (Regulationb) which sets out benchmarks for strengthening domestic extraction, processing and recycling of CRMs to enhance supply chain resilience, and the RESourceEU Action Plan (Communication from the Commission to) designed to secure sustainably sourced CRMs such as cobalt, lithium and rare earths across key industrial value chains. Decontamination technologies and processes are being improved and newly developed to enable a higher volume of plastic and composites to be recycled and reintegrated into the supply chain. This includes strategies to identify and separate hazardous substances to depollute material flows as well as, e.g., blockchain or other digital tracking technologies to certify the quality and compliance of recycled materials (*SSbD2* and *SSbD6*).

Creating SSbD awareness, demand, and traceability in the end-of-life vehicle sector requires shifting attention from headline recycling rates to the quality and value of recycled materials. Awareness increases when stakeholders recognise how *SSbD7* enables higher-value recycling through advanced sorting, quality assessment, and data-driven end-of-life management. Demand is strengthened when OEMs and recyclers embed *SSbD1* in design and procurement decisions by prioritising CRM-reduced components without compromising performance. Standardised DPPs under the ESPR (Regulation, 2024/1781) can enhance traceability and secure lifecycle data exchange (*SSbD8*), creating the transparency and market pull needed to accelerate a more circular, CRM-efficient, and SSbD-aligned automotive ecosystem.

Automotive Tires: The tire value chain faces significant sustainability challenges, including the reliance on natural rubber, the generation of microplastic pollution from tire wear, and limited options for end-of-life recycling. In response, innovation efforts are focusing on developing sustainable rubber alternatives, integrating recycled content into tire production, and advancing chemical recycling technologies to enable higher-value material recovery (supporting in particular *SSbD4* and *SSbD7*). Extended Producer Responsibility (EPR) schemes are critical for improving tire collection, traceability, and recycling rates.

Creating SSbD awareness, demand, and traceability in the tire sector starts with making the full value chain visible to highlight the environmental impacts associated with conventional tire production and use. Awareness-raising efforts should clearly communicate both the challenges and the benefits of SSbD-aligned solutions, such as sustainably rubber alternatives, higher recycled content, and emerging chemical-recycling pathways (*SSbD4* and *SSbD7*). Demand can be stimulated by embedding SSbD-related criteria into procurement policies, OEM specifications, and credible consumer-facing sustainability claims. Finally, strengthened traceability systems, which are supported by tools such as DPPs and EPR frameworks, enable reliable material tracking, open new end-of-life options (*SSbD7*), and help create the market pull needed to scale circular, low-impact tire innovations.

Moulded polyurethane (PU) foams play a vital role in automotive seating, providing comfort, durability, and safety while meeting strict industry standards. However, their reliance on fossil-based feedstocks contributes to CO_2 emissions, and their end-of-life recyclability remains a challenge due to their integration with metals and sensors in car seats. Applying SSbD strategies supports to overcome these sustainability issues through material innovation, including bio-based polyols from renewable sources (*SSbD4*) and recycled polyols derived from end-of-life foams (*SSbD4* and *SSbD7*). Additionally, energy-efficient manufacturing processes (*SSbD3*) help reduce environmental impact, while chemical recycling advancements offer new pathways for recovering raw materials (*SSbD7*).

Creating SSbD awareness and demand for moulded PU foams starts with a clear communication of sustainability challenges and the benefits of SSbD-aligned solutions (such as bio-based and recycled polyols, lower-energy production, and improved recyclability). Demand will be strengthened when OEM specifications and procurement criteria support these innovations. Traceability systems, including transparent material declarations, DPPs, and end-of-life tracking, enable verification, recovery, and reintegration of materials, supporting circular, next-generation PU foams.

Batteries: With the rapidly growing demand for batteries, it is a necessity that batteries are designed and manufactured in such a safe and sustainable way. Improvements are needed for instance to deal with unsustainable and unethical raw material extraction (contradicts *SSbD9*), high carbon footprint in manufacturing, thermal runaway and fire hazards, lack of robust battery management systems, and designs with sealed, glued, or welded ways that make disassembly dangerous (contradicts *SSbD7*). Incorporating sustainability as a critical criterion for the development of advanced materials for batteries is imperative. The focus is on increasing autonomy by boosting domestic production and reducing import dependence, and on researching and developing alternatives to CRMs. However, the substitution of CRMs in batteries (Li replacement by Na, Ca, Mg, etc.) is still at the cost of performance. The same applies for the substitution of polyvinylidene fluoride (PVDF) binders, possible source for PFAS (contradicts *SSbD2* and *SSbD6*); well performing solutions have not been found yet. The use of PFAS in battery manufacturing will come under particular scrutiny in the revision of REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals). Novel research is needed for improving the environmental processing for battery production with i) research on reduction of specific energy consumption and emissions (*SSbD3* and *SSbD5*), minimise the use of hazardous chemicals (*SSbD2* and *SSbD6*) and improving process and product safety, reduce cost including environmental ones, and increase efficiency and ii) validation of sustainable production processes and products in view of giga-scale application and to upgrade the degree of integration of sustainable manufacturing processes into the existing and future lines. For battery recycling, the adaptability and flexibility of existing recycling processes and the development of new ones i.e. direct recycling is needed, similar to the challenges of plastic and packaging recycling (*SSbD7*).

Creating SSbD awareness, demand, and traceability in the battery sector begins with clearly communicating the sustainability and safety challenges embedded in today's fast-growing battery value chains, from unethical raw-material extraction to high-carbon manufacturing, thermal-runaway risks and designs that hinder safe disassembly. Awareness increases when stakeholders clearly understand how SSbD principles guide solutions, including safer and more resource-efficient material choices (*SSbD1*), reduced use of hazardous substances such as PFAS, lower-carbon and energy-efficient production (*SSbD2* and *SSbD3*), and improved process and product safety (*SSbD6*). Building demand requires embedding these SSbD criteria into OEM requirements, standards, and funding mechanisms. Finally, robust traceability, supported by DPPs, responsible-sourcing verification, and end-of-life tracking, enables validation of SSbD performance, supports design for recycling (*SSbD7*), and accelerates the transition to sustainable, circular battery systems.

Green hydrogen is a key enabler of decarbonisation across multiple sectors, but its large-scale deployment requires overcoming challenges in production, storage, transport, and infrastructure. Transitioning from fossil-based hydrogen to renewable-powered electrolysis is essential (*SSbD4*), supported by innovations in storage, fuel cell efficiency and demands for chemical synthesis (*SSbD3*), as well as cross-sector collaboration to reduce costs and scale infrastructure. The sector currently relies on CRMs, including platinum group metals (Pt, Ir, Ru) and rare earth elements (Nd, Dy). To reduce CRM dependence, the development of low- or non-CRM catalysts (e.g. iron-based, bio-based (*SSbD4*), or organic catalysts) and ultra-low catalyst loadings for electrolysis and synthesis is crucial. Efforts are also underway to substitute PFAS-based fluoropolymers used in Proton Exchange Membrane (PEM) and Membrane Electrode Assemblies (MEA) components (*SSbD2* and *SSbD6*). Improving the safety, sustainability, and reliability of hydrogen refuelling infrastructure and equipment is essential to ensure the safe production, handling, and use of gaseous and liquid hydrogen, given its high flammability.

Creating SSbD awareness, demand, and traceability in the green-hydrogen value chain requires clear communication of sustainability and safety challenges linked to scale-up, including high renewable energy demand for electrolysis, dependence on CRMs (PGMs and rare earths), and the use of PFAS-based components. Demand is strengthened when OEMs, infrastructure developers, and public-sector buyers embed SSbD criteria into procurement, certification, and funding requirements, incentivizing low- or non-CRM catalysts, PFAS substitution, safer chemistries, and transparent supply chains (SSbD1, SSbD2, SSbD4). Robust traceability tools—such as Digital Product Passports, material tracking, and verification of PFAS-free components—enable monitoring of SSbD performance across production, storage, transport, and refuelling, supporting safety and reliability (SSbD6). Integrating lifecycle thinking and circularity by design, including improved recovery of PGMs and other CRMs where substitution is not yet feasible, further minimizes environmental impacts and supports long-term sustainable deployment (SSbD7, SSbD8).

Cost-effectiveness: At the product and design level, the main challenge for hydrogen technologies is the high cost of green hydrogen production from renewable sources (*SSbD4*) such as wind and solar. Although green hydrogen offers the highest environmental benefits, it is currently more expensive than conventional energy carriers, a gap that may narrow as fossil fuel prices increase due to resource constraints. Further advances are needed to reduce costs and improve efficiency across renewable hydrogen production pathways. Key priorities include the development of cost-efficient solutions for i) large-scale hydrogen production and storage, ii) materials and technologies enabling hydrogen transport through existing natural gas infrastructure, iii) hydrogen carriers, iv) innovative and hybrid compression technologies, and v) eco-design guidelines and resource-efficient manufacturing processes. The deployment of fuel cells, water electrolysers, and associated plant equipment is expected to scale rapidly, making early integration of cost-efficient and sustainable design essential.

Electronics for end-consumers: The electronics value chain faces critical challenges related to the sourcing of raw materials such as rare earth elements (related to *SSbD9*), and the growing volume of electronic waste (e-waste). Due to trade restrictions emerging in recent years, the availability of raw materials is constrained, and e-waste is still exported. In the long term, development of alternative supply chains may become significant, as it aligns with the resilience goals of the EU and allows for improved sustainability. Many materials relevant for semiconductors are process by-products recovered from extracting common materials, so building new supply chains is possible, but can be resource-intensive (*SSbD1*). Circularity of materials is hindered by the complexity of disassembling mixed-material devices as well as the high innovation rates as for composition and type of products. Innovations include modular designs for easier repair (*SSbD7*), closed-loop systems for rare earth element recovery, and enhanced e-waste recycling infrastructure. Collection from consumers, however, is a challenge. Regulatory frameworks like the Waste Electrical and Electronic Equipment (WEEE) Directive are playing a key role in driving improvements. Right-to-repair regulations in the EU and around the world are helping to motivate the manufacturers to design electronics for improved repairability and simplified disassembly. These design changes are enabling the reuse of some devices after repair/refurbishment or their disassembly at the end-of-life (*SSbD7*). Furthermore, automated and robotic technologies are being developed and deployed for dismantling consumer electronics that are produced in large numbers (e.g., mobile phones), which helps to separate individual components that are rich in particular materials (e.g., magnets or copper coils) for subsequent recycling. Incentive programs that subsidize the cost of repairs have proven effective in helping the individuals to choose the repair option.

Creating SSbD awareness, demand, and traceability in consumer electronics starts with making the hidden impacts of today's devices visible, from the social risks linked to rare-earth sourcing (*SSbD9*) to the mounting volumes of exported e-waste and the resource intensity of semiconductor materials (*SSbD1* and *SSbD3*). Awareness grows when manufacturers, retailers and consumers understand how *material efficiency (SSbD1)* and *responsible sourcing (SSbD9*) can reduce dependence on constrained supply chains, and why design choices that enable repair, refurbishment and disassembly (*SSbD7*) are essential for circularity. Demand is strengthened when right-to-repair rules, WEEE obligations and procurement criteria reward modular designs, closed-loop rare-earth recovery and high-quality recycling. Building traceability systems, including transparent material declarations, DPP and automated dismantling data, ensures that improved designs can be verified, components can be recovered, and circular value can be captured. Together, these measures create the market pull and accountability needed to shift consumer electronics toward safer, more sustainable and repair-friendly products.

Fragrances: The Fragrance industry has a long and successful track record of prioritising safety and sustainability, while allowing for innovation and creativity in fragrance creation. Key sectorial initiatives on fragrance safety are based on the IFRA standards, grounded in a rigorous risk assessment methodology conducted by the Research Institute for Fragrance Materials (RIFM), while sustainability initiatives are based on the IFRA-IOFI Sustainability Charter, promoting lifecycle approaches, sustainable sourcing (*SSbD9*), and carbon footprint reduction. Safe-by-design principles have been applied and have been evolving in the fragrance value chain for the past 20 years. Safety and safe use are key criteria for fragrances, and early screening and designing of safe fragrances for consumer use are nowadays at the core of innovation. Besides the hazard criteria of most harmful substances such as carcinogenic, mutagenic and reprotoxic (CMR), endocrine disruption, persistent, bioaccumulative and toxic (PBT/vPvB), persistent, mobile and toxic (PMT/vPvM), skin sensitization has a special focus because of consumer use of the end-products (*SSbD2 and SSbD6*). Additional specific sustainability criteria are e.g., i) deforestation, agricultural impact such as land and water use, and biodiversity for the fragrances sourced naturally, ii) restricted substances related to adverse human health effects at raw materials, production and use stages (*SSbD2* and *SSbD6*), iii) emissions to air, water and soil at production and use stages (*SSbD5*), and iv) energy consumption at the production stage especially for synthetically produced fragrances (*SSbD3*). Social criteria are, e.g., cultural heritage, small farmers, child labour, diversity and fair trade at the raw materials stage (*SSbD9*), community integration and work-life balance at the production stage, and affordability and consumer needs at the use stage, and appropriate disposal procedures at the end-of-life stage. Current key challenges include addressing data availability and balancing safety with sustainability requirements.

Creating SSbD awareness, demand, and traceability in the fragrance sector builds on an already mature culture of safety and responsible innovation, but it requires making the full set of sustainability and social impacts more visible across the value chain. The long-standing IFRA/RIFM system provides a strong foundation for minimizing the use and exposure to hazardous chemicals (*SSbD2* and *SSbD6*), especially through early screening for CMR, endocrine disruption, PBT/PMT properties and skin sensitization. Awareness grows when stakeholders understand how SSbD-related practices also connect with broader sustainability expectations such as preventing deforestation, reducing agricultural impacts, managing emissions (*SSbD5*) and improving energy efficiency in synthetic fragrance production (*SSbD3*). Creating demand depends on brands and retailers embedding SSbD principles into procurement and product-development briefs, rewarding responsibly sourced natural ingredients and low-impact synthetics, and valuing social criteria aligned with *SSbD9*. Strengthening traceability systems helps verify claims, support fair-trade supply chains, and ensure that safety and sustainability remain balanced as innovation accelerates.

3.4.2. *Reflection of value chain examples*

Across the diverse value chain examples presented, clear commonalities emerge in both the challenges and enablers of SSbD implementation. Despite differences in materials, markets and maturity, the examples demonstrate that SSbD uptake is rarely a purely technical issue; rather, it is shaped by value-chain complexity, regulatory signals, data availability, and coordination among actors.

A first shared pattern is the central role of hazardous substance substitution (*SSbD2* and *SSbD6*). Whether addressing PFAS in textiles and batteries, legacy admixtures in concrete, additives in plastics, or sensitising substances in fragrances, most sectors face similar tensions between functionality, safety and performance. Across sectors, short-term, regulation-driven substitution strategies risk regrettable substitutions, while longer-term, anticipatory approaches deliver more robust safety and sustainability benefits. This highlights the importance of shared chemical knowledge, screening tools and substitution roadmaps that can be transferred across sectors rather than developed in isolation.

A second cross-cutting theme is the challenge of CRMs dependence. Sectors such as batteries, automotive, electronics and green hydrogen are still highly dependent on CRMs, which are associated with environmental, social and supply-chain risks. Common responses include material efficiency, substitution with lower-criticality alternatives, and improved recovery and recycling at end-of-life. These shared challenges underline the value of cross-sector collaboration on CRM substitution research, recycling infrastructures and quality standards for secondary materials. Aligning CRM strategies across value chains can reduce criticality risks while supporting circularity, resilience and SSbD uptake.

A third strong similarity is the emphasis on design for circularity and end-of-life performance (*SSbD7*). Packaging, textiles, vehicles, tires, electronics, PU foams and batteries all struggle with material complexity, mixed materials and quality loss during recycling. In each case, solutions depend on early design choices, better material identification, and access to downstream data. These recurring challenges point to a clear opportunity for cross-sector collaboration on recyclability standards, quality criteria for recyclates, and shared approaches to material separation and decontamination, rather than sector-specific solutions that fragment markets.

Fourth, nearly all examples underline the growing importance of traceability and data transparency as enablers of SSbD. DPPs, chemical inventories, recycled-content verification and lifecycle data exchange appear repeatedly as critical tools to support regulatory compliance, build trust, and create market pull for SSbD-aligned products. Because these tools are being developed in parallel across many sectors, alignment on data structures, indicators and verification methods through cross-sector collaboration can significantly reduce implementation costs and accelerate learning.

A further shared insight concerns demand creation and procurement leverage. In nearly all value chains, SSbD uptake strengthens when downstream actors, e.g., OEMs, brands, retailers and public procurers, embed SSbD criteria into specifications and purchasing decisions. Cross-sector collaboration can help by developing common procurement criteria, performance benchmarks and credible sustainability claims, avoiding confusion and dilution of SSbD ambitions.

In summary, the value chain examples demonstrate that SSbD implementation is not only a technical exercise but a multi-actor, data-dependent, and regulation-shaped process. They highlight the need for cross-sector strategies that SSbD must address to become operational in practice.

4. Outlook

SSbD is at the interface between a scientific concept and industrial operationalisation. It should serve as a holistic guiding tool to steer innovation while preventing regrettable substitutions and be aligned with policy developments to prepare industry for upcoming transitions and regulations.

It is important to note that SSbD is often presented through tools, checklists, and databases, but reducing it to a procedural exercise misses its core purpose. At its heart, SSbD is a mindset—a way of approaching innovation that prioritises anticipation, responsibility, and systems thinking long before any formal assessment begins. Tools can support decisions, structure evidence, and reveal hotspots, yet they cannot replace the underlying orientation toward designing chemicals, materials, and products that are inherently safer and more sustainable across their entire lifecycle.

What distinguishes SSbD is not the number of approaches and tools applied, but the intentionality behind them: questioning assumptions, considering downstream impacts early, integrating uncertainty rather than ignoring it, and recognising that safety and sustainability are design parameters, not afterthoughts. In this sense, tools are enablers, not endpoints. SSbD requires a cultural shift toward proactive, iterative, and ethically grounded innovation - one that embeds precaution, circularity, and long-term societal value into the design process itself.

SSbD decisions need to be communicated in a transparent, understandable and verifiable way to build trust with clients, regulators and authorities, non-governmental organisations, academia and customers. This needs to be done with a long-term perspective not just based on a “one day” need or short-term advantage.

Incentives are needed to support good practices. These can be leveraged by European Funding Initiatives, Member State Engagement, or other programs and Initiatives (such as funding programs, workshops, and strategies to support eco-design, circular economy, and SSbD-specific research and development). The impact of these incentives extends beyond financial support, fostering new sustainable markets and a culture of innovation, collaboration, and environmental stewardship. By incentivizing the integration of safety and sustainability considerations into (new) chemical, material, and product design and development processes, these initiatives pave the way for a more resilient, resource-efficient, and environmentally conscious future.

Adopting SSbD brings significant *business benefits*. SSbD encourages companies to innovate by developing chemicals, materials, products, and processes that are both safe and sustainable. This can lead to breakthrough products that not only meet safety standards, but also offer improved performance, less raw material and energy needs, and reduced environmental impact. The SSbD framework is also closely aligned with upcoming regulatory changes. Companies that adopt this approach will therefore make their operations future-proof and position themselves as sustainability leaders, while supporting better EU strategic autonomy via better control of their supply chain. Chemical companies can enhance their reputation and appeal to environmentally and sustainability conscious consumers, employees, and investors. SSbD also helps companies balance safety and sustainability with cost- and social-effectiveness by assessing also socio-economic aspects. This ensures that innovations are not only more environmentally sustainable, but also economically and socially viable.

This study mapped the evolving SSbD landscape and aligned roadmaps, guidance, and implementation approaches with the different stages of the innovation process. While the 2025 revision of the SSbD framework significantly enhanced its clarity and operability for innovation and industrial uptake (e.g., through the introduction of SSbD principles, a more structured and scenario-based scoping analysis, clearer guidance on the tiered assessments, trade-off evaluation, uncertainty handling and documentation, and the expansion of the socio-economic dimension), this work further supports SSbD operationalisation. By combining good practices with sectoral value chain examples, it demonstrates how SSbD can effectively transition from a conceptual framework to an operational tool for industry. Embedding SSbD at corporate, managerial, and operational levels, supported by regulatory readiness and transparent data sharing, will accelerate Europe's transition toward sustainable, competitive, and resilient global markets.

CRediT authorship contribution statement

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Funding

IRISS receives funding from the European Union’s Horizon Europe research and innovation program under grant agreement no 101058245. UK participants in Project IRISS are supported by UKRI grant 10038816. CH participants in Project IRISS receive funding from the Swiss State Secretariat for Education, Research and Innovation (SERI).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scp.2026.102355.

Data availability

All data used in the article are presented either in the article or in the supplementary material.

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