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Original Article

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Safe and Sustainable-by-Design under the European Green Deal—regulatory readiness or pressure for companies?

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Abstract

The European Green Deal, popular for its "2050 climate neutrality" target, also postulates the "zero pollution ambition for a toxic-free environment," supported through the Chemicals Strategy for Sustainability (CSS). The CSS mentions Safe and Sustainable-by-Design (SSbD), calling for the integration of safety and sustainability into innovation. Developing the SSbD framework further is a key action enabling both CSS objectives and the broader Green Deal ambitions. Yet, SSbD's complexity and data demands are seen by many companies as burdensome, and the benefits of SSbD adoption remain unclear. Therefore, this study examines SSbD's role in "regulatory readiness," i.e., proactive development of novel chemicals, materials, and products for compliance before market entry and for adaptability to future regulations. By analyzing 15 EU policies (prioritized through industry feedback) against 15 SSbD components, this study finds a 64% overlap, i.e., many mandates for SSbD components are observed within the analyzed legislation. The findings of this study inform recommendations for industry and policymakers to foster industrial competitiveness in the European Union. Companies are recommended to leverage SSbD for early regulatory readiness, internalize SSbD's "fail early and fail cheap" philosophy, and invest in SSbD capacity building. Policymakers are recommended to incentivize corporate SSbD adoption, explicitly integrate SSbD into future legislation, and invest in research to address critical gaps in safety and sustainability sciences to strengthen SSbD further.

Keywords: EU Green Deal, clean industrial deal, Safe and Sustainable-by-Design (SSbD), regulatory readiness, regulatory pressure

Introduction

The European Green Deal (European Commission, 2019) is the European Union's (EU) strategic framework, best known for but extending far beyond its 2050 climate neutrality goal, guiding the EU's green transition through new and revised policies (CircuLaw, 2024; Fetting, 2020; Krämer, 2020; Leonard et al., 2021; Wolf et al., 2021). The Green Deal's "zero pollution ambition for a toxic-free environment" (European Parliament, 2022) is supported by the Chemicals Strategy for Sustainability (CSS; European Commission, 2020a). The CSS addresses chemical pollution across the full life-cycle of substances by promoting safe and sustainable use and phasing out substances of concern that threaten human health and ecosystems (Doak et al., 2022; Herzler et al., 2021; Scholz et al., 2022; van Dijk et al., 2021).

To support the safe and sustainable design and use of chemicals and materials under the CSS, the precautionary and proactive Safe and Sustainable-by-Design (SSbD) approach was introduced (European Commission, 2022). The SSbD approach contributes to the aims of the CSS to (i) steer the innovation process toward the green and sustainable industrial transition; (ii) minimize the production and use of substances of concern, in line with and beyond existing and upcoming regulatory obligations; and (iii) minimize the impact on health, climate, and the environment during sourcing, production, use and end-of-life (EoL) of chemicals, materials, processes, and (by extension) products. By integrating safety and sustainability considerations early in the innovation process, SSbD ensures that novel chemicals, materials, processes/technologies, and the products using them do not pose risks to human health or the environment, thereby aligning with the objectives of the CSS (Apel et al., 2024; Sudheshwar et al., 2024).

In 2022, the European Commission's Joint Research Center (EC-JRC) further developed the EC's SSbD framework (Caldeira et al., 2022). The European Commission subsequently published a recommendation to establish a European SSbD framework for

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chemicals and materials in research and innovation activities and to test it to improve its relevance, reliability, and operability (European Commission, 2022). Later in 2024, EC-JRC also published a methodological guidance (Abbate et al., 2024) explaining not only the rationale behind the framework, but also integrating the feedback collected during several stakeholder consultations, describing a method for scoping analysis, and discussing the importance of correctly framing subsequent SSbD assessments. All these efforts are culminating in an updated SSbD framework, with a draft now open for public consultation (Garmendia Aguirre et al., 2025). Given its breadth, SSbD has the potential to go beyond the CSS, addressing multiple areas and ambitions within the Green Deal. The SSbD framework can serve as an approach for aligning innovation and the development of future chemicals' and materials' lifecycles with existing and emerging legislative frameworks under the EU Green Deal. The holistic and interdisciplinary nature of the SSbD framework presents both opportunities and challenges in its execution and implementation. Feedback on SSbD highlights that it improves safety and sustainability performance, but it is effort-intensive, requires a high level of multidisciplinary expertise and data, and is time-consuming and expensive (Abbate et al., 2025; Caldeira et al., 2023; Leso et al., 2024; Pitaro et al., 2025).

Although SSbD remains a voluntary framework within the EU, it has gained formal recognition as one of the eco-design performance criteria under the EU's Ecodesign for Sustainable Products Regulation (ESPR; European Parliament, & Council of the European Union, 2024e). Established within ANNEX II of ESPR is the procedure for defining performance requirements for eco-design: "Any performance requirement concerning substances as referred to in Annex I, point (f), shall take into consideration existing chemical safety assessments performed by the relevant Union bodies for the substances concerned, as well as safe and sustainable by design criteria for chemicals and materials developed by the Commission."

These recent developments raise concerns for businesses operating in or exporting to the EU, given the previously discussed challenges associated with implementing SSbD. Industry stakeholders have called for clarity and guidance on "the role of SSbD versus existing EU legislation," "starting SSbD implementation," "SSbD implementation by small and medium enterprises," and "incentives for SSbD adoption" (see Chapter S1.1 of online supplementary material). Thus, businesses currently perceive SSbD as an additional burden in an already overregulated EU, potentially stifling innovation rather than fostering it (Caldeira et al., 2023; Leso et al., 2024; Sudheshwar et al., 2024).

This perception contrasts sharply with that of policymakers and academics, with Caldeira et al. (2022) arguing that SSbD reduces regulatory burden by ensuring "regulatory readiness" because it is designed to "steer the innovation process towards the green and sustainable industrial transition, substitute or minimize the production and use of substances of concern, in line with, and beyond existing and upcoming regulatory obligations." Academic literature does not provide a standardized definition of "regulatory readiness." However, consultants (Deloitte Center for Financial Services, 2017) describe it as the proactive adaptation to existing regulations while also anticipating future regulatory changes. The term "compliance readiness" is often used interchangeably with "regulatory readiness," although they seem to differ slightly. "Compliance readiness" refers to an organization's preparedness to meet and adhere only to current regulatory requirements, industry standards, and legal obligations, with less emphasis on anticipating or adapting to future regulatory changes (Secora Consulting, 2025; Socium Security, 2024).

To advance SSbD and foster safe(r) and (more) sustainable innovation, it is essential to bridge the differing perspectives of corporations and policymakers. Specifically, it remains unclear whether SSbD poses additional regulatory pressure or offers a pathway to regulatory readiness for companies. To address this gap, we investigated the reciprocal relationship between SSbD and EU policies through two questions:

1. *Does SSbD help companies achieve regulatory readiness in the EU?* This examines whether SSbD aligns with existing legal requirements, reducing compliance burdens, or whether misalignments create additional regulatory pressures, particularly under frameworks like the ESPR.
2. *Can EU policies guide and support SSbD implementation?* This assesses how existing policies facilitate and inform SSbD adoption by stakeholders.

To this end, we analyze 15 sector-specific and cross-cutting environmental policies under the EU Green Deal to determine which SSbD components they address and to what extent. Although previous studies have briefly explored connections between specific EU policies and SSbD, these efforts had a limited scope. Abbate et al. (2024) highlighted potential synergies between SSbD and socioeconomic assessments mandated by EU policies. The European Commission: Directorate-General for Research and Innovation (2021) mapped existing policies and initiatives to inform sustainable-by-design criteria development. Reins and Wijns (2025) also analyzed the implications of SSbD for achieving circular economy objectives in the EU. Moreover, Garmendia Aguirre et al. (2025) reference EU chemical regulations relevant to safety assessments within the updated SSbD framework draft. Most recently, Schwirn et al. (2025) presented an initial overview of synergies, illustrating how SSbD can bridge innovation and EU legislation. However, as Schwirn et al. (2025) also acknowledged, an in-depth analysis examining SSbD across the broad range of EU Green Deal policies is currently absent. This research gap likely fuels corporate skepticism toward and policymakers' faith in the regulatory implications of SSbD.

Background: EU policy context and SSbD

EU Green Deal, CSS, and the Clean Industrial Deal

The European Green Deal (European Commission, 2019) is the EU's strategic policy framework aimed at fostering a fair and prosperous society with a sustainable economy, prioritizing both citizen well-being and environmental protection (Fetting, 2020). Although widely recognized for its 2050 climate neutrality target (CircuLaw, 2024; Krämer, 2020), the Green Deal's scope extends far beyond this goal (Leonard et al., 2021; Wolf et al., 2021). Rather than a single legislative act, it represents a comprehensive framework guiding the EU's green transition through the development and implementation of strategies that inform policy revisions and new legislative initiatives (Fetting, 2020).

Central to the Green Deal is its "zero pollution ambition for a toxic-free environment," advanced through the Chemicals Strategy for Sustainability (CSS) Towards a Toxic-Free Environment (European Commission, 2020a). This ambition targets zero pollution by 2050, ensuring that pollution levels in air, water, and soil do not harm human health or the environment (European Parliament, 2022) and remain within planetary boundaries (Persson et al., 2022; Richardson et al., 2023). To address chemical pollution, the CSS serves as the EU's regional strategy focusing on the entire lifecycle of chemicals, including their design through SSbD. The CSS seeks to promote safe and sustainable use of chemicals and to minimize and substitute the use of substances of concern that pose chronic health risks to humans and ecosystems (Doak et al., 2022; Herzler et al., 2021; Scholz et al., 2022; van Dijk et al., 2021). Thus, SSbD is an operational approach for achieving the objectives of the CSS, with the CSS itself supporting the broader Green Deal ambitions.

Exemplifying the rapidly evolving policy landscape, a new plan for Europe's sustainable prosperity and competitiveness was recently published within the Clean Industrial Deal (Leyen, 2024; President of the European Commission, 2025). Building on the Green Deal's foundations with a more targeted approach, it recognizes the urgency of simultaneous decarbonization and industrialization. The strategy outlines five key objectives: (i) a more circular and resilient economy, (ii) boosting productivity through digital technology diffusion, (iii) placing research and innovation at the economy's heart, (iv) turbo-charging investment, and (v) tackling skills and labor gaps (Leyen, 2024). The Clean Industrial Deal shares notable synergies with SSbD, because both aim to promote innovation and competitiveness within European industry while advancing the Green Deal's goals of sustainability, circularity, and pollution prevention. Given the evolving policy landscape, it remains to be seen how SSbD—including the planned updates of the framework (Garmendia Aguirre et al., 2025)—will be positioned for future industrial competitiveness within the EU.

The SSbD framework and design principles

The SSbD framework proposed by the EC-JRC in 2022 (Figure 1) consists of two components: the (re)design phase and the assessment steps. For the (re)design phase, the framework proposes a nonexhaustive list of design principles to support the integration of SSbD considerations and provide qualitative guidance for integrating safety and sustainability into innovation. These design principles build on concepts such as green chemistry (Anastas & Warner, 1998), green engineering (Anastas & Zimmerman, 2003), circular chemistry (Keijer et al., 2019), sustainable chemistry (UBA, 2009, 2016), benign-by-design (Boethling et al., 2007; Kümmerer, 2007; Kümmerer & Hempel, 2010), design-for-recycling (Hummen & Sudheshwar, 2023; Kriwet et al., 1995; Kümmerer et al., 2020; Reuter, 2011; Sudheshwar et al., 2023), and eco-design (Knight & Jenkins, 2009; MacDonald & She, 2015; Vallet et al., 2013; Van der Ryn & Cowan, 2013).

The quantitative side lies in the five SSbD assessment steps. Steps 1–3 focus on human and environmental safety, and Steps

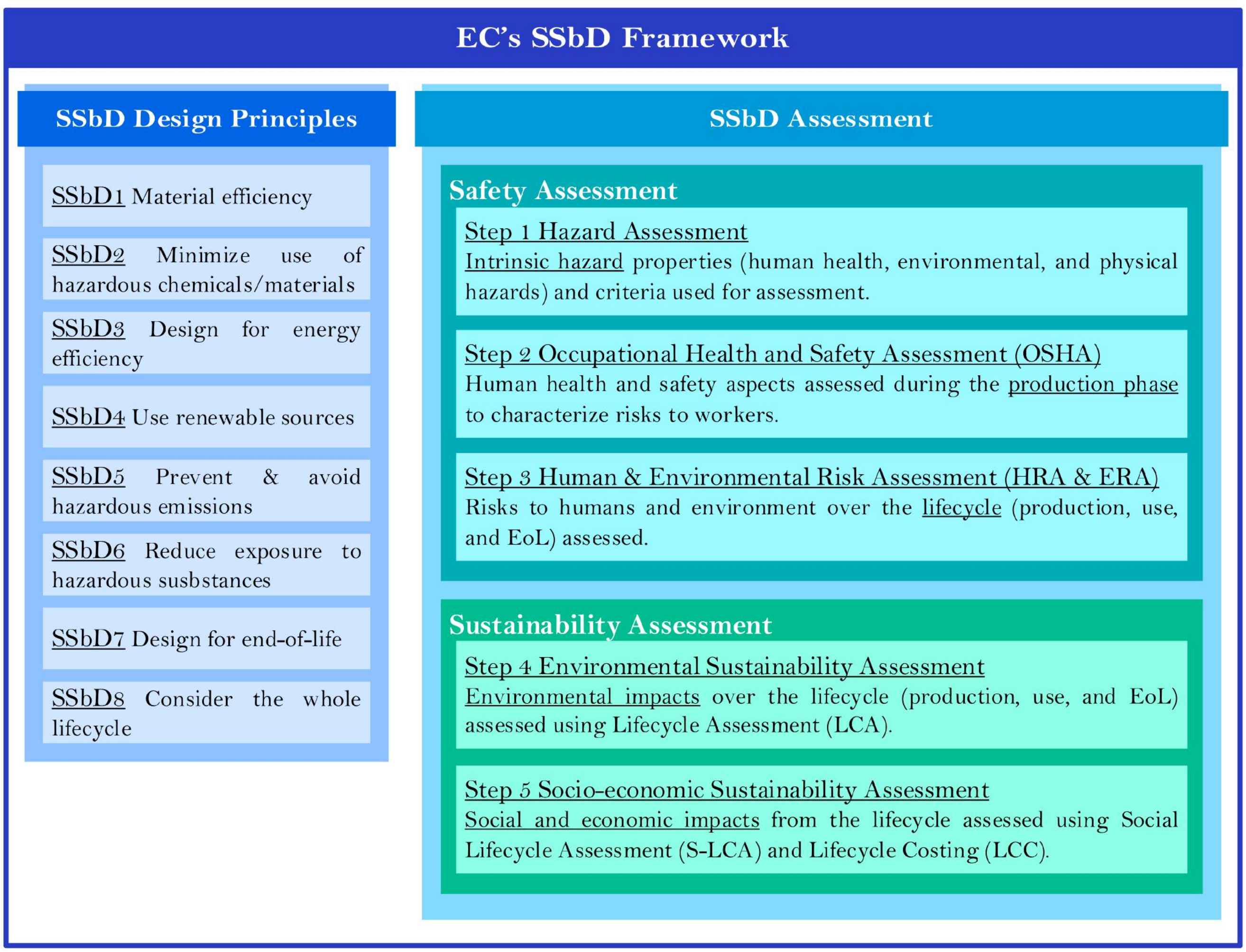

Figure 1. Overview of the Safe and Sustainable-by-Design (SSbD) framework from 2022 as proposed by Caldeira et al. (2022) and European Commission (2022). While the assessment steps were initially intended to be followed sequentially, this is no longer required; instead, as clarified by Abbate et al. (2024) in the latest methodological guidance on SSbD and by Garmendia Aguirre et al. (2025) in the updated draft of the SSbD framework, SSbD assessments are now understood to be tiered and iterative, allowing for varying levels of completeness (simplified, intermediate, or full) as the maturity of the innovation increases.

4–5 extend to environmental, social, and economic sustainability (Purvis et al., 2019). In the draft of the updated SSbD framework (Garmendia Aguirre et al., 2025), these steps are no longer sequential but can be applied in parallel.

Safe and Sustainable-by-Design emphasizes early innovation, particularly the (re)design phase, to anticipate and mitigate risks, prevent market entry of harmful substances, and avoid long-term "lock-ins" (Blumenthal et al., 2022; Purvis et al., 2019). Implementing SSbD during innovation—design, prototyping, and upscaling—is favorable because supply chains and processes remain flexible and may be optimized for safety and sustainability, ensuring a smoother market launch (OECD, 2020; Soeteman-Hernández et al., 2020).

The scope of SSbD extends beyond its role in the CSS. Its safety assessments address pollution, and its sustainability assessments encompass climate and biodiversity effects, positioning SSbD as an approach to tackle the triple planetary crisis of climate change, biodiversity loss, and pollution (Hellweg et al., 2023; Larsen & Tararas, 2024). By addressing energy and material efficiency, circularity, and social and economic aspects, SSbD provides a holistic framework for sustainable innovation and can help create a more sustainable future with fewer regrettable outcomes (Bréchet & Jouvet, 2009; Gray & Rivkin, 1991; Pottier & Nguyen-Huu, 2020).

Methods

Policy selection and classification

In the first step, all legislation under the EU Green Deal were compiled from online resources (CircuLaw, 2024) and cross-checked against legislation cited in key SSbD documents published by Abbate et al. (2024), Garmendia Aguirre et al. (2025), European Commission: Directorate-General for Research and Innovation (2021), and Caldeira et al. (2022). To narrow the focus, three survey and feedback rounds were held with academics, regulators, and industry stakeholders to identify and prioritize the most relevant policies for analysis. As described in Chapter S1 of the online supplementary material, the process began with a preliminary list of EU legislation, which was then scored and ranked by participants during the subsequent feedback rounds. These rankings formed the basis for selecting the final set of policies. Given that the EU Green Deal encompasses more than 150 pieces of legislation (CircuLaw, 2024), prioritizing a subset of key and relevant policies was essential to enable a detailed and feasible policy analysis. Since compliance with these regulations is primarily the responsibility of industry, industrial participation in the prioritization process was critical for assessing the role of SSbD in regulatory readiness. Contributions from industry associations across the EU's chemicals, automotive, energy, electronics, textiles, fragrance, packaging, and construction chemicals sectors (see *Acknowledgments*) were especially valuable, not only shaping the policy selection but also actively encouraging the initiation of this analysis.

Ultimately, this analysis concentrates on 15 key pieces of legislation, detailed in Table 1, along with the rationale for their inclusion. Table 1 includes legislation ranging from older provisions to those set to be enforced in the future. For the analysis, only EU directives, regulations, laws, and acts were considered, as these are legally binding. Although there are distinctions—for instance, EU regulations are uniformly applicable across all member states, whereas EU directives are transposed into national laws to achieve the directives' objectives—both are legally enforceable (European Commission: Directorate-General for Communication, n.d.-b). In contrast, EU agendas, recommendations, opinions, strategies, and other soft policy instruments lack legal enforceability and thus were excluded from the analysis (European Commission: Directorate-General for Communication, n.d.-a).

Figure 2 conceptually illustrates the varying scopes of the analyzed legislation. Some legislation exclusively cover specific sectors; for instance, the New Batteries Regulation (NBR) exclusively applies to batteries and is "sector-specific." In contrast, legislation such as the Corporate Sustainability Reporting Directive (CSRD) apply across all sectors and are thus categorized in Figure 2 as "overarching-environmental legislation." Given that SSbD focuses on safety and sustainability, strong synergies with overarching environmental regulations are expected. However, this policy analysis also included sector-specific legislation, because they were of particular interest to industry stakeholders, subsequently prioritized during feedback rounds, and provided insights into the alignment of sectoral trends and requirements with SSbD.

Additionally, the scope of EU legislation ranges from lower levels, such as chemicals and materials, to higher levels, such as entire companies, supply chains, and nations. Figure 2 presents these levels hierarchically, where lower levels are nested within higher ones. For example, the product level encapsulates processes (both manufacturing and waste management) as well as the chemicals and materials used in the product. This conceptual differentiation in policy scopes recognizes that higher-level assessments require data derived from lower levels. For example, corporate assessments depend on the evaluation of products, which in turn require assessments of constituent processes and materials and chemicals. Policies may also span multiple levels; for instance, the Waste Framework Directive (WFD) and Packaging and Packaging Waste Regulation (PPWR) address both various products (including their waste) and processes (recycling, EoL treatments, and waste management). Another way to approach Figure 2 is by examining where in the value chains are the various pieces of legislation applicable. For example, regulations such as Classification, Labeling, and Packaging (CLP) and Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) apply to chemicals and materials, which are typically upstream in a value chain. In contrast, legislation focusing on products, like the ESPR, apply further downstream.

Selection of voluntary corporate initiatives

In addition to EU Green Deal legislation, industrial stakeholders recommended examining potential synergies between SSbD and voluntary corporate sustainability initiatives. These initiatives are particularly relevant given their global prominence (also beyond the EU) among companies aiming to lead in sustainability and corporate reporting practices. Based on suggestions from industry stakeholders (see online supplementary material Chapter S1), the following widely adopted frameworks were separately analyzed: recommendations from the Taskforce on Climate-related Financial Disclosures (TCFD, 2023), the Science-based Targets Initiative (SBTi, 2024), and the Taskforce on Nature-related Financial Disclosures (TNFD, 2024).

Policy analysis

Before the policy analysis, the original SSbD framework proposed by Caldeira et al. (2022), as summarized in Figure 1, was simplified into 15 components, encompassing both the design principles and the SSbD assessments, as outlined in Table 2. Although the number of SSbD design principles remained unchanged, the number of SSbD assessment steps increased due to the subdivision of Steps 3 and 5. During a preliminary review of the policies, it became clear that many required only human or environmental risk assessment, but not both. As a result, Step 3 was divided

Table 1. The 15 EU legislation analyzed in the context of SSbD and ordered based on their scopes depicted in Figure 2. Codes are not available (N.A.) for legislation that are yet to be enforced.

Legislation	Acronym	Code	Description	Status	Rationale for consideration
1. Classification, Labeling, and Packaging of substances and mixtures (European Parliament, & Council of the European Union, 2008b)	CLP	1272/2008, 2024/2865	- Defines and harmonizes hazard classification criteria for substances and mixtures. - Hazard class and information should be disclosed on the packaging through the relevant labels. - Established an inventory of substances with their classification and labeling.	Amendment in force since December 10, 2024	Key legislation for hazard classification in the EU
2. Registration, Evaluation, Authorization and Restriction of Chemicals (European Parliament, & Council of the European Union, 2006)	REACH	1907/2006	- Companies responsible for managing risk from and disclosing safety information regarding chemicals. - Chemicals with production/use larger than 1 ton/year should be registered within the European Chemicals Agency (ECHA) database (ECHA, 2024). - Authorization of chemicals and restrictions on their use imposed.	In force since 2007	Legislation forming basis of chemical safety assessment and risk management option analysis in EU
3. Ecodesign for Sustainable Products Regulation (European Parliament, & Council of the European Union, 2024e)	ESPR	2024/1781	- All physical products placed on EU markets should fulfill the eco-design requirements stipulated in the regulation for improved sustainability and circularity. - Digital product passport (DPP), rules to deal with unsold inventory, and clause for green procurement of goods and services included in the regulation.	In force from July 18, 2024	New(er) legislation stipulating key eco-design and sustainability requirements for products
4. Waste Framework Directive (European Parliament, & Council of the European Union, 2008a)	WFD	2008/98/EC	- Stipulates waste management principles and waste reuse, recycling, and recovery targets to protect human health and environment. - Establishes the EU "waste hierarchy," polluter pays principle, and extended producer responsibility (EPR).	In force since 2008	General waste management legislation in the EU
5. Packaging and Packaging Waste Regulation (European Parliament, & Council of the European Union, 2024g)	PPWR	2025/40	- Harmonizes management of plastic waste across EU member states. - Sets recycling targets for different kinds of packaging. - Lists measures to minimize, reuse, recycle, and safely dispose packaging waste.	In force from February 11, 2025	Important directive on packaging in the EU
6. New Batteries Regulation (European Parliament, & Council of the European Union, 2023)	NBR	2023/1542	- Defines sustainability, safety, labeling, marking, and information required to place batteries on the EU market. - Improved sourcing of raw materials for and better collection,	In force from August 17, 2023	New(er) legislation on batteries covering many safety and sustainability aspects

(continued)

Table 1. (continued)

Legislation	Acronym	Code	Description	Status	Rationale for consideration
			recycling and repurposing at end-of-life of batteries mandated.		
7. Waste from Electrical and Electronic Equipment Directive (European Parliament, & Council of the European Union, 2012)	WEEE	2012/19/EU	- Mandates separate collection of e-waste and stipulates targets for collection, recovery, and recycling. - Harmonizes WEEE reporting and targets illegal export of e-waste from the EU.	Originally enforced in 2003	Critical e-waste management law
8. Right-to-repair Directive (European Parliament, & Council of the European Union, 2024c)	R2R	2024/1799	- Promotes repair of broken and defective products over replacement. - Improves accessibility, transparency, and attractiveness of repair services.	To be enforced from July 31, 2026	New(er) legislation pertaining to circular economy through repairability
9. Industrial and Livestock Rearing Emissions Directive (European Parliament, & Council of the European Union, 2024b)	IED 2.0	2010/75, 2024/1785	- Targets emissions to air, water, and land from industries and animal farms in the EU. - Establishes pollution compliance requirements including industrial emission limits, disclosure, and targets.	In force from August 4, 2024	Key legislation dealing with pollution from industries in the EU
10. EU Taxonomy Regulation (European Parliament, & Council of the European Union, 2020)	EUtax	2020/852	- Stipulates conditions under which an economic activity may qualify as environmentally sustainable and in alignment with the EU Green Deal objectives. - Climate change mitigation and adaptation, sustainable use and protection of fresh and marine water, transition to circular economy, pollution prevention and control, and protection and restoration of biodiversity defined as environmental objectives.	In force from July 12, 2024	Defines sustainable activities in the EU and relevant for industry/corporates
11. Green Claims Directive (European Commission, 2023b)	GrCl	N.A.	- Targets greenwashing. - Stipulates clear criteria to ensure reliable, comparable, and verifiable information for environmental claims and labels.	To be enforced	Relevant for industry/corporates
12. Corporate Sustainability Reporting Directive (European Parliament, & Council of the European Union, 2022)	CSRD	2022/2464	- Large companies and listed small and medium enterprises operating within the EU required to report on aspects related to sustainability for investors. - Emphasis on how corporate business models address, tackle, and leverage sustainability targets, risks, and opportunities, respectively. - Reporting in accordance with European Sustainability Reporting Standards (ESRS) (EFRAG, 2022).	In force from January 5, 2023	EU-wide sustainability reporting regulation relevant for companies

(continued)

Table 1. (continued)

Legislation	Acronym	Code	Description	Status	Rationale for consideration
13. Corporate Sustainability Due Diligence Directive (European Parliament, & Council of the European Union, 2024a)	CSDDD	2024/1760	- Large companies operating within the EU required to ensure that no adverse human rights violations and environmental impacts occur due to their operations. - Companies to (establish processes for and) conduct due diligence across their value chains and subsidiaries.	In force from July 25, 2024	EU-wide sustainability reporting regulation focusing on supply chains of companies
14. Critical Raw Materials Act (European Parliament, & Council of the European Union, 2024d)	CRM	2024/1252	- These provisions list critical and strategic raw materials, set benchmarks for their 2030 domestic capacities, aim to create secure and resilient supply chains, aid in supply risk preparedness and mitigation, improve circularity and sustainability of raw materials, and diversify raw material imports.	In force from May 23, 2024	Key legislation for energy and materials sectors
15. Nature Restoration Law (European Parliament, & Council of the European Union (2024f)	NatRes	2024/1991	- Sets binding targets to restore degraded ecosystems to increase biodiversity, ecosystem services, limit global warming, and build resilience. - Focus also on ecosystems that can capture and store carbon.	In force from August 18, 2024	Only compiled legislation focusing on ecosystems and biodiversity

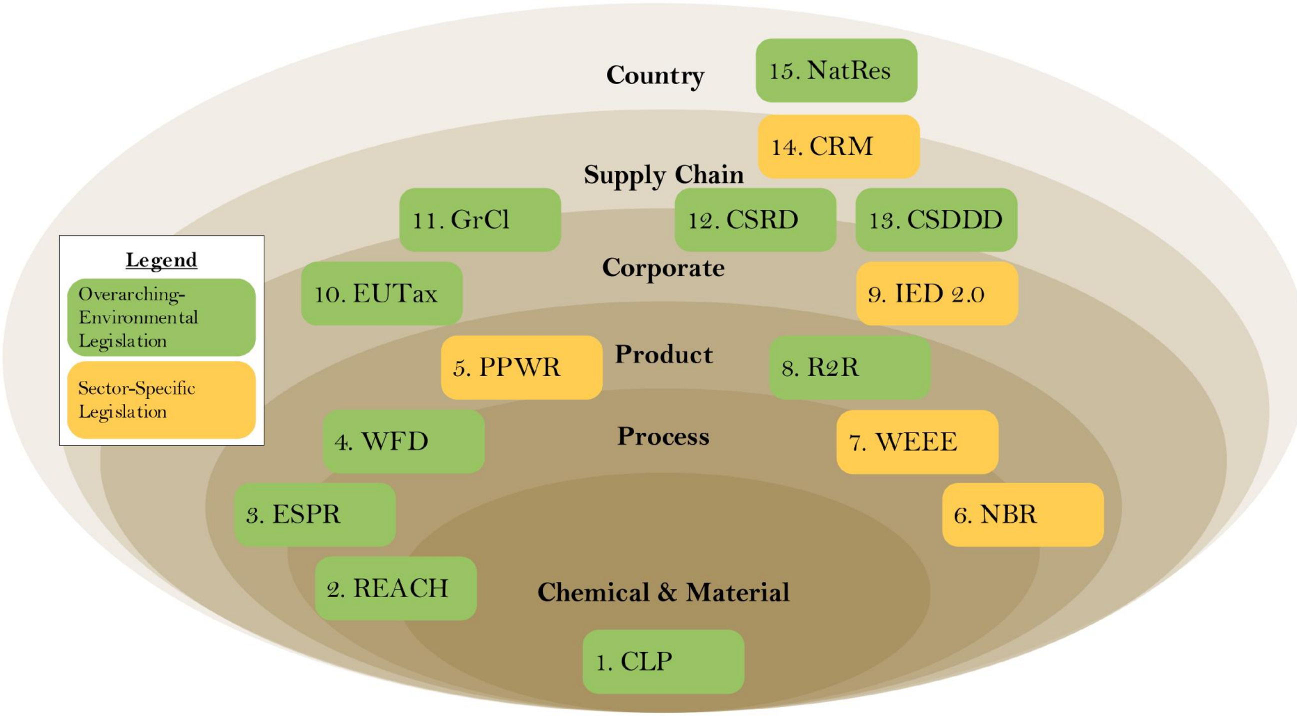

Figure 2. The 15 EU legislation (abbreviations in Table 1) with differing scopes analyzed in the context of SSbD and classified into overarching environmental and sector-specific legislation. While this schematic offers a valuable overview and understanding of the policies, it may have exceptions and not be universally applicable. For instance, the placement of supply chains below countries in the hierarchy may not accurately represent the complexity of international supply chains that often span multiple national borders.

Table 2. The 15 SSbD components examined across various policies during the analysis.

Design principles		Safety assessment		Sustainability assessment	
Identifier	**Component**	**Identifier**	**Component**	**Identifier**	**Component**
SSbD1	Material Efficiency	Step 1	Hazard	Step 4	Environmental
SSbD2	Minimize Hazard Use	Step 2	Occupational Safety & Health	Step 5.1	Social
SSbD3	Energy Efficiency	Step 3.1	Environmental Risk	Step 5.2	Economic
SSbD4	Use Renewable Sources	Step 3.2	Human Risk		
SSbD5	Avoid Hazard Emission				
SSbD6	Reduce Hazard Exposure				
SSbD7	Design for end-of-life				
SSbD8	Lifecycle Thinking				

into Step 3.1 for environmental risk and Step 3.2 for human risk. Similarly, Step 5 of the SSbD assessment was split into Steps 5.1 and 5.2 to separately address social and economic assessments, respectively. These distinctions in Steps 3 and 5 were necessary for a precise policy analysis. Although the updated draft framework (Garmendia Aguirre et al., 2025) no longer sequentially numbers assessment steps, Table 2 and the subsequent analysis retain this convention for clarity and consistency, because the core SSbD assessments remain unchanged within the updated SSbD draft.

An EU legislation typically consists of a preamble, enactus (articles), and annexures (referred to within the articles). For the policy analysis, only the legally binding enactus and annexes were considered. Although the preambles often provide insight into the legislative intent and contain multiple references relevant to SSbD components, they were excluded from the analysis because they are not legally binding.

The essential objective of the policy analysis was to test the relationship between the SSbD components and the EU legislation, tabulated in Tables 1 and 2, respectively. To do so, a set of multiple synonymous keywords corresponding to each SSbD component were identified through a preliminary review of the legislative texts. These keywords, detailed in Chapter S2 of the online supplementary material, were then used to extract relevant clauses from the policy texts. Policy texts and clauses relevant to SSbD and its components were documented and then further analyzed to map out the linkages between the policy texts and the SSbD components. The detailed analysis can be found in Chapter S3 of the online supplementary material. Based on the analysis, the SSbD components can be embedded within the compiled legislation in four distinct ways:

- **No Link** indicates that the keywords failed to extract any relevant information, reflecting that the respective SSbD component was not mentioned in the legislation's enacting provisions. Overinterpretation of the policy text was avoided; unless an explicit instruction related to an SSbD component was identified, the legislation was "not linked" to that SSbD component. For example, REACH has no links to environmental sustainability since it does not mandate lifecycle assessments, carbon footprinting, or environmental footprinting.
- **Mandate Present** implies that the keyword search successfully identified that the SSbD component is "mandated" within the legislation's articles. A mandate can be direct—explicitly stated in the articles—or indirect, implied as necessary to meet certain requirements outlined in the articles. For example, the ESPR includes the reduction of risks to human health and the environment as an eco-design requirement. Consequently, the ESPR indirectly mandates Steps 3.1 and 3.2 of the SSbD assessment, because risk reduction inherently requires risk evaluation.
- **Criteria Defined** means that a legislative mandate for an SSbD component includes specific implementation details—such as quantitative targets, thresholds, or concrete objectives—that provide actionable guidance. In this policy analysis, we use "criteria" exclusively to refer to these legislative details. This usage differs from how "criteria" appears in the SSbD framework itself (e.g., hazard criteria in Step 1). To avoid confusion: when a policy "defines criteria" for an SSbD component, the policy provides specific legislative requirements or targets for implementation. For example, the ESPR establishes explicit hazard thresholds based on CLP and REACH classifications, thereby defining criteria for Step 1 of the SSbD assessment. Similarly, the WFD and WEEE directive include quantitative recycling targets, thus defining criteria for SSbD7 (design for EoL).
- **Tools Described** denotes that in addition to mandates and criteria, the legislation also explicitly prescribe "SSbD tools" such as methods, approaches, or standards. This relationship was only applicable for SSbD assessments, which are typically quantitative and may be conducted with the prescribed tools, as opposed to the more qualitative design principles. A clear example is REACH, which specifies tools for chemical safety assessments corresponding to Steps 1–3 of SSbD assessment.

The four aforementioned categories map the nuanced relationships between SSbD components and EU legislation. Detailed examples of mandates, criteria, and tools prescribed by policies for SSbD components are provided in Chapter S4 of the online supplementary material. In this assessment, the strength of the linkage or relationship between an EU legislation and an SSbD component follows the order: no link < mandate present < criteria defined < tools described. For a specific legislation, "no links" to SSbD components implies that SSbD does not provide regulatory readiness. Conversely, the more mandates, criteria, and tools within a policy, the greater the level of regulatory readiness that SSbD can provide. Furthermore, legislation stipulating criteria and tools can provide valuable guidance and support to stakeholders in implementing SSbD components.

Industry feedback on policy analysis results

After the completion of the policy analysis, the results were presented for feedback in March 2025 to the industry associations and researchers who contributed to the policy prioritization process. This policy analysis was initiated in response to the industry's need to better understand the linkages between SSbD and EU policy. Thus, this final feedback round aimed to evaluate the relevance and practical value of the findings for the companies and businesses represented by the industrial associations.

Results

SSbD for regulatory readiness

The results of the policy analysis are visualized in the heatmap presented in Figure 3, illustrating the reciprocal relationship between SSbD components and EU legislation. To assess whether SSbD offers regulatory readiness, the heatmap should be interpreted horizontally for each legislation. When read this way, the presence of any form of a link or mandate (indicated by any green cell) demonstrates regulatory readiness. As long as the cell does not indicate "no link," the test for regulatory readiness may be considered positive. Overall, 64% of the cells (145 out of 225) show some form of mandate for specific SSbD components—marked as "mandate present," "criteria defined," or "tools described" (with the latter two inherently implying a mandate). This suggests that the SSbD framework does provide a meaningful level of regulatory readiness across the policies analyzed.

Some policies exhibit broader coverage across the 15 SSbD components. Notable legislation with relationships to 12 or more SSbD components include ESPR (12/15), PPWR (13/15), WFD (13/15), NBR (14/15), Industrial and Livestock Rearing Emissions Directive (IED) 2.0 (12/15), Corporate Sustainability Reporting Directive (CSRD) (12/15), and Critical Raw Materials Act (CRM) (14/15). The SSbD framework provides greater regulatory readiness for sector-specific legislation such as NBR, IED 2.0, and CRM, because these policies often address multiple environmental aspects relevant to their respective sectors. In contrast, overarching environmental regulations tend to focus on specific environmental issues (i.e., SSbD components) and may therefore exhibit fewer total linkages to SSbD components. For example, CLP (9/15) explicitly describes tools for hazard classification but does not cover sustainability.

Equally important is considering legislation with limited SSbD linkages. Most notably, the Right-to-repair Directive (R2R) legislation exhibited no relationship with any SSbD components in our analysis. Although the legislation focuses on improving product reparability and circularity—objectives aligned with SSbD (and ESPR) principles—its (enforceable) article clauses lack the specificity required for inclusion in the heatmap.

Legislation supporting SSbD

Beyond testing whether a relationship exists between legislation and SSbD components, it is equally important to assess the quality of such relationships. Legislation providing criteria or tools over mandates is more relevant to SSbD. Therefore, when addressing the second research question—how legislation can support stakeholders with SSbD implementation—the heatmap in Figure 3 should be read vertically to check for criteria and tools corresponding to SSbD components (evident from hotspots in the heatmap). These criteria and tools can serve as initial reference points for practitioners, providing guidance on implementing SSbD components.

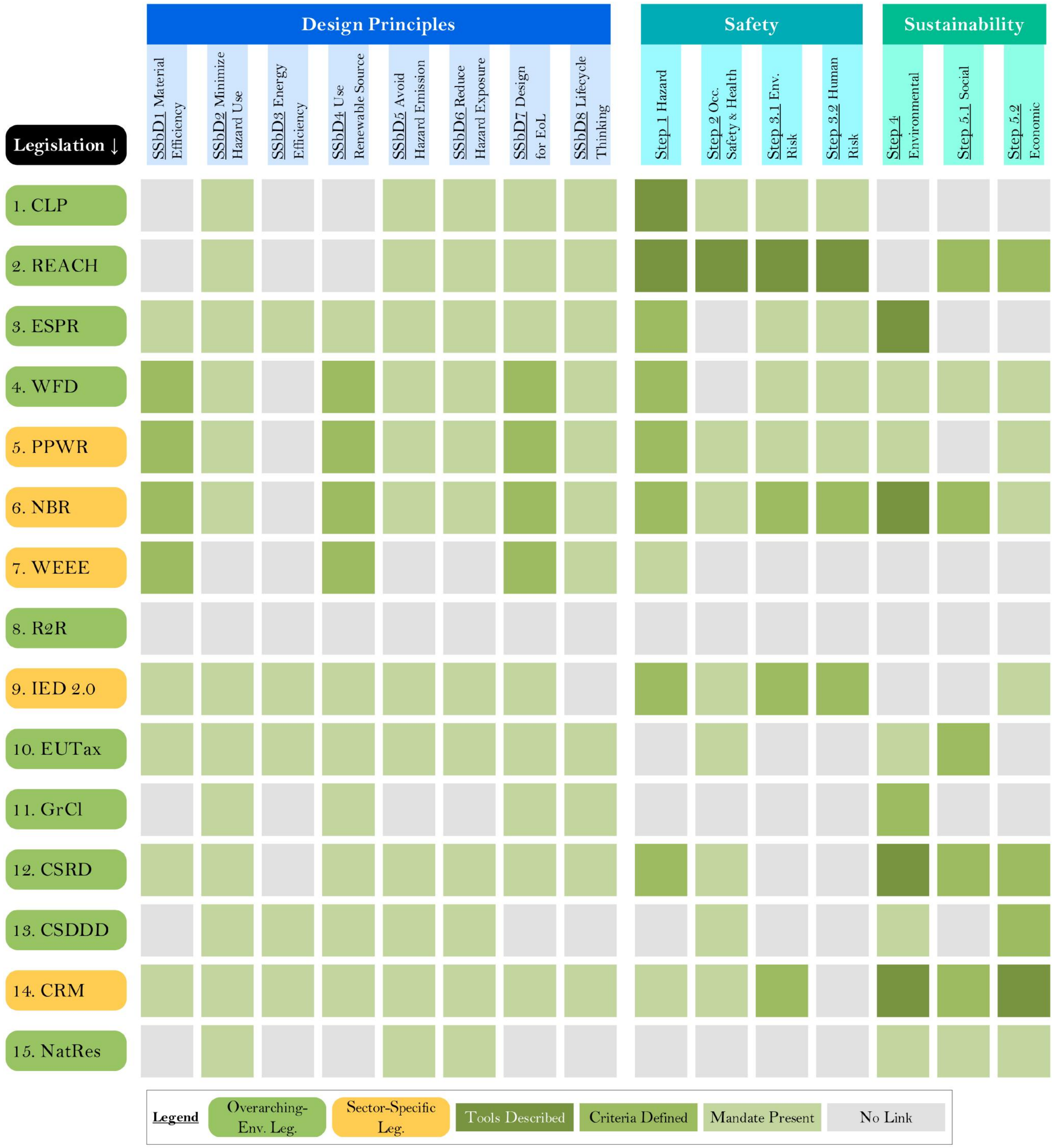

Figure 3. A 15 × 15 heatmap illustrating the reciprocal relationships between the selected EU legislation (abbreviations in Table 1) and Safe and Sustainable-by-Design (SSbD) components. Kindly note the abbreviations for occupational (occ.). legislation (leg.) and environmental (env.).

Figure 3 illustrates that the criteria for SSbD design principles are particularly well defined in legislation addressing waste management and EoL considerations. For example, WFD, PPWR, NBR, and Waste from Electrical and Electronic Equipment (WEEE) all address waste management by stipulating material recycling, reuse, and recovery targets, which can be interpreted as criteria for design principles SSbD1, SSbD4, and SSbD7. Although this legislation also mandates other SSbD principles, criteria (including targets and objectives) are not provided for design principles beyond SSbD1, SSbD4, and SSbD7.

Moreover, tools have been defined for environmental safety assessments, with CLP forming the basis for hazard assessment across the EU and REACH supplementing it with tools for occupational safety and health, along with risk assessments. Also, legislation with the scope "product" and beyond (Figure 2) such as ESPR, NBR, CSRD, and CRM also explicitly stipulate tools for environmental sustainability assessments.

Planned and conditional mandates

After the policy analysis, numerous instances of planned and conditional mandates for specific SSbD components were identified. Planned mandates refer to the gradual evolution of a policy over time. In EU legislation, specific timelines are established for the potential inclusion of certain SSbD components after an assessment of their necessity. This approach reflects policymakers' intent to avoid abruptly overwhelming affected companies and institutions, instead opting to refine and strengthen environmental assessments as policy adoption matures. For example, the evaluation of potential benefits from incorporating social sustainability assessments (Step 5.1) within the ESPR is scheduled for 2028. Similarly, there is a proposal to include socioeconomic (Step 5.1 and 5.2) and environmental sustainability assessments (Step 4) within the WEEE directive. Since these planned mandates are contingent on future assessments of their relevance, their inclusion in EU legislation remains uncertain and is not guaranteed. Therefore, Figure 3 groups planned mandates under "no link," to avoid speculation and capture only the current state of EU policies.

On the other hand, conditional mandates pertain to the scope and applicability of legislation, i.e., legislation or articles apply under specific conditions. For instance, REACH applies only to chemicals produced in volumes exceeding 1 ton per year. Likewise, the CSRD applies solely to large EU companies that meet specific criteria. Another notable example is the socioeconomic assessment (Step 5.1 and 5.2) required under REACH, which is mandated only when seeking authorization to use an identified SVHC and to demonstrate that "socio-economic benefits outweigh the risk to human health or the environment arising from the use of the substance." These cases highlight that both legislation and their articles are not universally applicable but instead take effect under specific conditions. Because Figure 3 aims to present an overarching summary, it does not capture the nuances of conditional mandates, which are instead grouped under the label "mandate present." However, further analysis of conditional mandates would be valuable in assessing whether full adherence to the SSbD framework might lead to compliance overpreparedness and inefficiency. Additional examples of both planned and conditional mandates can be found in Chapter S3 of the online supplementary material.

Voluntary corporate initiatives

A review of the CSRD document and the accompanying European Sustainability Reporting Standards (ESRS) (EFRAG, 2022; European Commission, 2023a) revealed significant overlap with the voluntary initiatives (TCFD, SBTi, and TNFD), to the extent that the latter are effectively mandatory within the EU after the enactment of the CSRD. Since the ESRS comprehensively embed these voluntary frameworks, a detailed mapping against SSbD was deemed unnecessary because it would duplicate the analysis already conducted for the CSRD.

The ESRS E1 Climate Change standard under the CSRD requires companies to report how their business models align with the Paris Agreement targets, which matches the commitment required under SBTi to limit global warming to 1.5 °C by reducing greenhouse gas (GHG) emissions by 50%. Additionally, ESRS E1, similar to TCFD recommendations, incorporates the concept of double materiality, requiring companies to disclose both how their activities contribute to climate change and how they are impacted by climate-related risks, opportunities, and challenges. Furthermore, the ESRS E4 Biodiversity and Ecosystems standard under the CSRD, which aligns with TNFD requirements, mandates disclosures on how a company's operations affect global biodiversity and ecosystems, as well as how biodiversity-related impacts, risks, and opportunities affect the business.

Industrial feedback on results

The results of the policy analysis generated significant interest and constructive feedback from industry associations (see *Acknowledgments*). Industrial representatives particularly appreciated Figure 3, because it clearly illustrates the overlaps between SSbD components and EU legislation. For companies operating in the EU, the findings were considered both informative and educational, helping to clarify the regulatory relevance of SSbD. Importantly, participants noted that the visualization of regulatory readiness through the heatmap could support internal advocacy for SSbD within companies. Specifically, it could help researchers communicate the value of SSbD to nontechnical stakeholders and company management more effectively. One participant remarked that the heatmap likely reflects the EU's upcoming approach to environmental policymaking—first standardizing environmental safety and sustainability through SSbD and then progressively integrating or referencing individual SSbD components in future regulations.

There was some criticism as well. Some industry associations noted the absence of very specific sectoral legislation. While understanding the need to limit the analysis to 15 policies for feasibility, they expressed strong interest in future analyses with an expanded scope considering additional sector-specific legislation.

Discussion

SSbD and EU legislation

The results of this analysis highlight that SSbD not only may support companies with regulatory readiness, but also that legislation may support stakeholders in SSbD implementation. Many legislative frameworks serve as repositories of tools or guidance documents that can facilitate the implementation of specific SSbD components. Likewise, data produced during SSbD implementation can be used to meet regulatory requirements, and data from regulatory processes can, in turn, support SSbD efforts. Although this policy analysis could have investigated additional legislative mandates for the entire SSbD framework, doing so would be premature given the novelty of SSbD. Apart from the explicit mention of "safe and sustainable by design criteria for chemicals and materials" in the ESPR, none of the reviewed legislation directly reference SSbD. This omission is primarily because most EU legislation predate the SSbD framework. As a result, explicit integration of SSbD would only be feasible through future legislative amendments. This is significant because, although SSbD is a scientific rather than a policy framework, it has the potential to drive the development of future policies, embodying the principle of science-driven policy (Joint Research Centre, n.d.; UNEP, 2024). By encouraging policymakers to adopt SSbD thinking, SSbD can serve as a catalyst for the creation of new policies and support the harmonization of existing and emerging legislation by providing a unifying framework.

Despite the lack of explicit references to the entire SSbD framework, some legislation covers many SSbD components. For example, ESPR, the EU Taxonomy, and CRM include mandates that align with all SSbD design principles, as depicted in Figure 3. Similarly, NBR requires both safety and sustainability assessments, covering all SSbD assessment steps. These cases are noteworthy, and they demonstrate how certain legislation are beginning to mandate simultaneous assessments of safety and sustainability—a trend that could further support their integration into generic and legislative decision-making processes in the future.

It is essential to distinguish between specific SSbD components (bits and pieces of SSbD) versus the full (entire) SSbD framework. Although SSbD consists of multiple components, as listed in Table 2, their interrelationship is what defines the SSbD framework. Thus, legislative mandates for individual components do not equate to a mandate for SSbD as a whole. For instance, although compliance with REACH ensures the absence of major safety risks, it does not cover environmental sustainability assessments and thus does not constitute full SSbD adoption. Overlaps between SSbD components and legislative requirements are particularly relevant for assessing regulatory readiness. Due to these shared elements, companies implementing SSbD are likely to generate the necessary data (such as risk assessments for REACH) well before reaching formal compliance stages. This early alignment supports regulatory readiness by streamlining the path to compliance.

When examining the EU Green Deal as a policy mix, the literature (Friege et al., 2019; Johansson & Krook, 2021; Pender et al., 2024; Pfeffer et al., 2025) highlights inconsistencies between resource efficiency and circular economy legislation on one hand and hazardous waste management regulations on the other. These contradictions create waste management and circularity challenges when dealing with contaminated secondary raw materials and hazardous substances during EoL. However, from an SSbD perspective, there appears to be a trend toward greater coherence, congruence, and consistency across policies. Coherence refers to the logical coexistence of multiple policy goals, congruence denotes the mutual reinforcement of goals and instruments, and consistency ensures that policy tools support rather than undermine each other (Howlett & Rayner, 2007, 2013, 2018). Recent amendments and newly introduced policies more clearly reference upstream legislation, such as CLP and REACH, as well as methods for environmental sustainability assessments. This suggests that the ongoing refinement of environmental safety and sustainability assessment methods is leading to their growing recognition and progressive integration into legislation by policymakers.

SSbD's biodiversity challenge

Biodiversity and ecosystems reporting from companies is required within the CSRD. Additionally, the EU's Biodiversity Strategy (European Commission, 2020b; Hermoso et al., 2022) and the Nature Restoration Law establish clear, time-bound targets for habitat restoration, reinforcing the central role of biodiversity and ecosystems in environmental compliance within the EU. However, following the SSbD framework alone may not yet provide companies with sufficient regulatory readiness for biodiversity assessments and reporting.

Within the SSbD framework, biodiversity impact assessment is intended as a part of environmental sustainability assessments. This means that lifecycle assessments (LCAs) address damages from supply chains (including lifecycles) to ecosystem quality caused by ecotoxicity, acidification, eutrophication, climate change, and land occupation or conversion—factors recognized as major drivers of biodiversity loss (Jaureguiberry et al., 2022). However, other approaches to biodiversity impact assessment also exist. The TNFD recommendations—and, by extension, the ESRS—prescribe spatial and ecosystem service assessment methods for biodiversity-related reporting. The TNFD recommendations also incorporate endpoint indicators for biodiversity health, such as spatial assessments of changes in land, freshwater, and ocean ecosystem conditions. As noted in the SSbD framework (Caldeira et al., 2022), these types of assessments are currently excluded from SSbD due to their limited operational maturity.

Additionally, the SSbD framework does not yet sufficiently address the biodiversity impacts caused by exposure to chemicals, despite its central role in the CSS, and the well-recognized link between chemical pollution and biodiversity loss (Groh et al., 2022; Sylvester et al., 2023). One major challenge in assessing these impacts lies in the enormous number of chemicals society relies on—Wang et al. (2020) identified more than 350,000 substances and mixtures registered globally for production and use. Each of these not only requires individual assessments, but the need to evaluate mixtures of chemicals adds to the complexity. Thus, data gaps and unresolved methodological issues, such as modeling the fate, transport, and exposure of chemicals, as well as the difficulty of aggregating local and regional impacts using spatiotemporal approaches, significantly hinder efforts to incorporate biodiversity impacts into SSbD. For example, within LCAs for chemicals, many impact categories relevant to biodiversity are still underdeveloped. The Environmental Footprint (EF) method (recommended method for SSbD Step 4) currently focuses on freshwater organisms for ecotoxicity assessments, whereas comprehensive ecotoxicity evaluations should also address impacts on terrestrial, marine, soil, and sediment organisms. Despite these challenges, biodiversity protection and reducing ecosystem damage from chemicals remain critical goals for the SSbD framework, although they are currently addressed only at a conceptual level until methods are further refined and operationalized. The SSbD framework acknowledges these gaps and highlights ongoing efforts to integrate LCA with Natural Capital Accounting to develop more comprehensive biodiversity impact assessment methods (Caldeira et al., 2022; Patinha Caldeira et al., 2022).

Thus, the biodiversity assessment challenge is not unique to SSbD but rather a research gap that extends more broadly to environmental sciences and corporate sustainability overall. The TNFD recommendations also face similar issues, as the biodiversity field remains in an evolving and maturing phase, with improvements necessary across all assessment methodologies (Heydari et al., 2020; Raar et al., 2020).

Operationalization of SSbD for companies

Although the SSbD framework supports regulatory preparedness for selected policies, its practical implementation and broader promotion remain unresolved challenges. A key barrier to embedding SSbD in corporate innovation lies in the limited availability of data during early innovation stages—both in terms of safety and sustainability. This is compounded by difficulties in obtaining high-quality primary LCA data, a lack of methodological guidance and scientific expertise, and the absence of predictive tools that can evaluate safety and sustainability performance when time and data are scarce. Its wide-ranging scope, limited tool availability, and ambitious goals make SSbD implementation complex, costly, and uncertain (Abbate et al., 2025; Caldeira et al., 2023; Leso et al., 2024; Sudheshwar et al., 2024).

Still, when evaluating costs, it is crucial to adopt a broader perspective. The short-term financial burdens that SSbD places on companies must be weighed against the long-term societal costs of pollution and public health impacts. The case of per- and polyfluoroalkyl substances (PFAS), also known as "forever chemicals," illustrates this. Health-related costs from PFAS have been estimated at €52–84 billion annually in the European Economic Area (Obsekov et al., 2023) and $60 billion in the United States, while environmental monitoring could cost up to €170 billion

(Goldenman et al., 2019). The U.S. Water Works Association estimates PFAS removal from drinking water could reach $370 billion (Rivard & Wolman, 2022). Although PFAS are priced at roughly €19/kg on the market, their actual cost to society is estimated at €18,700/kg (Perkins, 2023). Beyond this, producers and users also face direct costs from bans and the search for alternatives. If SSbD principles had been applied when PFAS were first introduced, their spread might have been limited, potentially avoiding today's economic and environmental burdens to both companies and society.

By integrating safety and sustainability early in the innovation process, companies internalize costs that would otherwise remain external—raising short-term R&D expenditures. Yet, this can reduce future compliance costs and increase competitiveness. Safe and Sustainable-by-Design is designed to facilitate market entry for sustainable innovations while minimizing the risk of regulatory bans and sunk investments. Its "fail early and fail cheap" approach not only prevents financial losses but also supports long-term business viability. Hence, SSbD innovations are more likely to withstand evolving regulations and strengthen corporate resilience and competitiveness (Soeteman-Hernández et al., 2025).

To accelerate the adoption of SSbD, SSbD innovation in companies should be incentivized—starting with potential measures such as compliance relief, patent extensions, or fast-track authorizations—which would support both the development of SSbD methodologies and the market entry of compliant products. As previously emphasized, aligning SSbD with compliance is essential for companies to realize immediate and tangible benefits. At present, the costs of SSbD may not yet be offset by regulatory readiness and may even exceed typical compliance expenditures. Therefore, companies that adopt SSbD and drive planet-centric innovation should be rewarded, encouraging broader uptake and fostering tool development (Apel et al., 2024; Soeteman-Hernández et al., 2024, 2025).

A stepwise approach is advisable for integrating SSbD into corporate innovation, beginning with well-established criteria that can be shared and interpreted across value chains. Importantly, SSbD is not an obscure concept. It is widely recognized within the EU chemical industry, as evidenced by the competing SSbD framework developed by the European Chemical Industry Council (CEFIC, 2021, 2024a, 2024b). This SSbD approach follows distinct steps based on industrial priorities. However, the ESPR currently references only the SSbD framework developed by the EC-JRC for evaluating eco-design performance criteria.

Enforceability of mandated SSbD components

Validating the implementation of certain SSbD components mandated by legislation (see Figure 3) may be difficult. For example, the ESPR mandates a reduction in human and environmental risks but does not define specific methods or tools for risk quantification and mitigation. This lack of clear guidance creates ambiguity, making it difficult to assess whether the chosen risk assessment approaches are appropriate or compliant (i.e., valid). However, regulators and compliance experts suggest otherwise, emphasizing that all legislation should be viewed in the context of the broader policy mix rather than in isolation (Rogge & Reichardt, 2016). Consequently, safety assessments under ESPR are not ambiguous, as REACH and CLP compliance are mandatory across the EU and serve as the foundation for downstream legislation, including ESPR. Although not explicitly stated, according to compliance and regulatory experts, it is implied that risk (safety) assessments required under ESPR should align with REACH standards.

The situation differs for SSbD design principles (SSbD1 to SSbD8) and sustainability assessments (Steps 4 to 5.2), where ambiguity could lead to regulatory loopholes and enforcement challenges. These components lack clearly defined tools, criteria, or strong legal foundations, increasing the risk of inconsistent application. To mitigate this, it is crucial to harmonize the interpretation and implementation of SSbD components across EU legislation. Establishing clear guidelines on appropriate tools and including liability clauses in relevant legislation would help reduce legal uncertainty. Typically, legislative misuse in the environmental sector is identified through legal proceedings and judicial precedents as well as public accusations—often driven by nongovernmental organizations (NGOs), consumer advocacy groups, or other civil society actors (Vanhala, 2018). However, determining the proper implementation of mandated SSbD components—such as the appropriate design and sustainability assessment approaches—may be excessively niche for legislators and challenging to adjudicate (Nilsson, 2004). Therefore, establishing clear and science-based regulatory guidance, including transparency at all levels and steps, is crucial to ensuring consistency and legal certainty for companies applying SSbD for regulatory readiness.

Limitations and opportunities

The current policy analysis is not without its limitations. It assessed only 15 legislative frameworks, around 10% of the roughly 150 laws included, amended, or drafted under the EU Green Deal (CircuLaw, 2024). Full coverage was not feasible, so the selection prioritized policies most relevant to SSbD—particularly those on chemicals, materials, processes, and products—while also including policies such as the EU Taxonomy and Green Claims Directive to explore SSbD's relevance to downstream sectors.

A specific challenge is the ever-evolving policy landscape, which makes static policy analyses prone to obsolescence. For example, the PPWR replaced the EU Packaging Directive during the study, requiring updates to the analysis, while the Omnibus initiative (European Commission & Council of the European Union, 2025a, 2025b), although not affecting the results, altered CSRD and Corporate Sustainability Due Diligence Directive (CSDDD) scopes after the analysis concluded. Future analyses may also need to account for changes such as socioeconomic assessments under ESPR. The upcoming SSbD framework update (Garmendia Aguirre et al., 2025) further highlights the "obsolescence" challenge. While it shifts from hazard-based and hierarchical SSbD approach to parallel safety and sustainability assessments, the implications for the present analysis are minimal because it focuses on SSbD's core elements, which are largely retained in the update.

Finally, the evolving policy context is exemplified by the new Clean Industrial Deal (Leyen, 2024; President of the European Commission, 2025). The Clean Industrial Deal and SSbD share goals of innovation, competitiveness, and sustainability, but SSbD's role within the Clean Industrial Deal and Europe's future industrial competitiveness is still unfolding.

Recommendations for companies and policymakers

The preceding discussion addresses diverse perspectives and practical considerations, which are synthesized below as targeted recommendations for companies and policymakers.

1. Recommendation for companies:
   - Leverage SSbD for early regulatory readiness by generating required compliance data during the design phase and future-proofing innovations against evolving regulations

- Internalize the "fail early and fail cheap" philosophy to minimize risks of regulatory bans, sunk investments, and future compliance costs, recognizing that prevention is significantly cheaper than remediation for both companies and society
- Invest in capacity building to address data gaps, improve quality of SSbD assessments, and develop predictive tools for early-stage innovation

2. Recommendations for policymakers:
- Incentivize SSbD adoption through compliance relief, patent extensions, or fast-track authorizations, ensuring short-term economic viability for companies
- Explicitly integrate SSbD components in future legislation as regulatory compliance requirements and recognize SSbD as a unifying framework to harmonize existing and emerging policies (e.g., Clean Industrial Deal), improving policy coherence, congruence, and consistency
- Invest in research to address critical gaps in safety and sustainability assessments (e.g., biodiversity impacts from chemical exposure), and further develop clear, science-based metrics, tools, and guidance for implementing SSbD

Conclusion and outlook

The policy analysis found strong alignment between SSbD and EU Green Deal legislation, with regulations such as ESPR, PPWR, WFD, NBR, IED 2.0, CSRD, and CRM showing the most overlap. Therefore, SSbD offers regulatory readiness by preparing innovations for compliance before market entry, while some EU policies also provide practical guidance and tools for implementing specific SSbD components. However, compliance readiness alone does not reduce pressure on companies, underscoring the need for continued collaboration among companies, policymakers, and regulators. To drive SSbD adoption, its value—such as competitiveness and cost savings—must be emphasized, supported by short-term incentives, with long-term integration into the Green Deal and Clean Industrial Deal.

Supplementary material

Supplementary material is available online at *Integrated Environmental Assessment and Management*.

Data availability

Data supporting the findings of this study are available within the article and its online supplementary material.

Author contributions

Akshat Sudheshwar (Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft), Christina Apel (Visualization, Writing—review & editing), Klaus Kümmerer (Writing—review & editing), Lya G. Soeteman-Hernández (Visualization, Writing—review & editing), Johanna Scheper (Investigation, Writing—review & editing), Andreas Falk (Investigation, Writing—review & editing), Annika Batel (Writing—review & editing), Jochen Markard (Writing—review & editing), Claudia Som (Conceptualization, Writing—review & editing), Zhanyun Wang (Supervision, Visualization, Writing—review & editing), and Bernd Nowack (Funding acquisition, Supervision, Writing—review & editing)

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Conflicts of interest

The authors have no conflicts of interest to declare.

Ethical disclaimer

This study relied on feedback collected through online surveys. While the participants were known to the researchers, all responses were recorded and analyzed in an anonymous form, ensuring that no individual could be identified through their answers. Participation was voluntary, and no sensitive or personally identifying information was collected. The study posed no risks beyond those encountered in everyday life, and the aggregated results were subsequently shared with the participants. In line with institutional guidelines and internationally recognized ethical standards, such as the Declaration of Helsinki, research of this nature—voluntary, minimal risk, and based on anonymous responses—qualifies for exemption from formal ethical review.

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Declaration of generative AI use

The authors used Grammarly and ChatGPT to polish this article and enhance its readability. The authors further reviewed and edited the content as needed and take full responsibility for the publication's content.

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