






Screening sustainability assessment of innovative bio-based solutions for art restoration within the EC SSbD framework

M. Menegaldo ^a , E. Giubilato ^b, L. Pizzol ^b, A. Zabeo ^b, E. Badetti ^a , E. Semenzin ^{a,*} 

^a Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University of Venice, Scientific Campus, via Torino 155, Mestre, Venice, 30172, Italy

^b GreenDecision s.r.l., Cannaregio 5904, Venice, 30121, Italy

A B S T R A C T

Implementing the EC Safe and Sustainable by Design (SSbD) framework from the early design phase of innovative solutions remains challenging. Although various methods to evaluate safety and sustainability exist, their integration throughout the innovation process, especially during the early stages at low Technology Readiness Levels (TRLs), is often hindered by time constraints, limited resources, the need for multidisciplinary expertise, and uncertainty in data availability and quality.

This study presents the Screening Sustainability Assessment (SSA), a screening-level method developed to support early-stage innovation by integrating functionality, safety, and sustainability aspects in product design. The SSA combines semi-quantitative scoring with targeted SSbD-oriented questions, enabling structured assessment across all life cycle stages. Each aspect is evaluated through specific criteria and questions, scored on a five-level scale, fostering informed stakeholder dialogue and supporting the early integration of SSbD objectives. The SSA was applied to assess two innovative bio-based protective coatings against a fossil-based benchmark. These products are intended for the preventive and remedial conservation of cultural heritage surfaces, a sector where traditional materials often present limitations in terms of durability, and sustainability performance. The application of the SSA method to the case study demonstrates its effectiveness in identifying SSbD performance and critical areas for improvement throughout the product life cycle. Although designed for the cultural heritage sector, the methodology is transferable to other fields facing similar challenges. It contributes to the broader goal of operationalizing the SSbD framework by offering a tool for embedding safety and sustainability considerations into innovation processes from the outset.

1. Introduction

In the framework of the European Green Deal, the European Commission has outlined a strategic vision for achieving a non-toxic, circular and climate-neutral economy (EC, 2019). This ambition is supported by key policy initiatives, including the Chemicals Strategy for Sustainability (CSS) and the Zero Pollution Action Plan, which collectively promote the integration of safety, sustainability and circularity into chemical and material innovation from the earliest stages of design (EC, 2021). A central component of this policy shift is the Safe and Sustainable by Design (SSbD) approach. In 2022, the Joint Research Centre (JRC) released a voluntary framework for the SSbD assessment of chemicals and materials (Caldeira et al., 2022), supported by a Recommendation from the European Commission (European Commission, 2022).

The SSbD approach has also laid the foundation for regulatory developments beyond the chemical sector, including the adoption of the Ecodesign for Sustainable Products Regulation (ESPR), which extends sustainability requirements to a broad range of products placed on the EU market (European Parliament and Council of the European Union, 2024).

Ideally, the SSbD Framework should be applicable from the early design phase, when the most impactful decisions on material selection and formulation are made (Garmendia-aguirre, Rasmussen, and Rauscher, 2025). However, the practical implementation of the SSbD framework presents notable challenges (Abbate et al., 2024). Full application often requires substantial time, specialized expertise, and access to detailed data on production processes, exposure scenarios, and life cycle impacts (Apel et al., 2024). These constraints can hinder the adoption of such framework in real-world contexts, particularly during the early stages of innovation or within small-scale research projects. Actually, a lot of methods to assess safety and sustainability exist, but applying them throughout the innovation process is quite challenging, mostly due to uncertainties during the innovation process itself, as well as the limited resources and data, especially at lower Technology Readiness Level (TRL) (Abbate et al., 2025; Pitaro et al., 2025).

To overcome these limitations, recent research has focused on the development of simplified tools and screening-level approaches that can support early decision-making. For example, Pizzol et al. (2023) proposed a methodology based on qualitative criteria and expert judgment to identify potential safety and sustainability issues under limited-data

* Corresponding author.

E-mail address: semenzin@unive.it (E. Semenzin).

conditions. More recently, [Arias et al. \(2024\)](#) proposed a composite indicator that integrates SSbD and circularity dimensions to assess emerging technologies under conditions of uncertainty. Their approach offers a structured yet practical tool to support preliminary evaluations when quantitative data are unavailable or incomplete.

While much of the focus has been placed on industrial and technological applications, these challenges and opportunities are highly relevant also in more specialized sectors, such as the conservation of cultural heritage ([Pinheiro et al., 2024](#)). In recent years, advancements in materials science and green chemistry have fostered innovation in this field, leading to the development of advanced formulations for the controlled cleaning, consolidation, and protection of artistic and historical artefacts ([Baglioni et al., 2015](#); [Casini et al., 2023](#)). Despite this progress, materials and techniques traditionally used for both remedial and preventive conservation still present significant limitations in terms of durability, sustainability, and cost-effectiveness. They are often based on energy-intensive processes and petroleum-derived substances that are neither environmentally friendly nor inherently safe ([Lazzara and Fakhrullin, 2019](#)). Moreover, these materials are frequently applied in indoor environments, placing conservators at risk of chronic or acute exposure to hazardous substances ([Brunelli et al., 2021](#)). Furthermore, the waste generated from conservation activities—often including rinsing fluids, residual chemicals, and contaminated tools—is rarely subject to formal environmental management, contributing to additional sustainability concerns ([Balliana et al., 2016](#)).

In response to these challenges, bio-based alternatives have gained growing attention in the cultural heritage sector ([Baglioni et al., 2021](#)). Derived from renewable resources such as plant biomass or natural polymers, these materials are designed to reduce dependence on fossil inputs while enhancing environmental compatibility ([European Commission, 2007](#)). However, as in other sectors, the adoption of innovative bio-based materials introduces new uncertainties regarding safety and sustainability performance, especially when such aspects cannot yet be fully characterized due to limited empirical data ([Bennich and Belyazid, 2017](#)).

To address this gap, the present work introduces a screening-level methodology tailored to the conservation of cultural heritage, developed and tested within the framework of the HEU GREENART (Green Endeavour for Art Restoration) project (GA No. 101060941). This assessment approach was specifically designed to be applicable during the early stages of product development, when data may be incomplete or unavailable. The proposed methodology allows for the integrated assessment of functionality, safety and sustainability aspects.

This study contributes to the broader objective of making the SSbD approach operational by proposing a transferable, semi-quantitative screening methodology tailored for application in the early stages of product design. Although developed in the context of cultural heritage conservation, the approach is intended to be applicable to other sectors facing similar challenges, where comprehensive data are lacking and early-stage assessments are needed to support informed, sustainability-oriented decision-making.

2. Methods

2.1. Life cycle safety and sustainability assessment

The Screening Sustainability Assessment (SSA) method is conceived as a practical tool to support the early-stage evaluation of innovative materials and products for cultural heritage conservation. It addresses the need for a structured, yet flexible, approach to decision-making during the design phase—when comprehensive data are typically unavailable, but key choices regarding composition must be taken, alongside a preliminary reflection on potential trade-offs between functionality, safety and sustainability performance.

The SSA is part of a broader assessment approach designed to support the development of safe and sustainable solutions through a three-stage

process. The first stage of this approach involves a preliminary hazard assessment, which focuses on identifying any potential human health, environmental or physical hazards based on the intrinsic properties defined under the CLP and REACH regulations of substances and formulations. This stage serves to flag substances of concern and guides safer material selection.

The second stage, described in detail here, consists of a semi-quantitative screening assessment, the SSA method, that integrates multiple criteria to evaluate and compare newly developed solutions with existing benchmarks. The SSA method builds on the NanoRestArt framework ([Semenzin et al., 2019](#)) and is aligned with Steps 2 and 3 of the European Commission's Safe and Sustainable by Design (SSbD) framework ([C Caldeira et al., 2022](#)). It enables a structured comparison of alternative materials or formulations, supports the identification of trade-offs, and facilitates the selection of the most promising options for further development.

Finally, the third stage involves a life cycle-based sustainability assessment, combining Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) to quantify the environmental and economic impacts of selected products across their entire life cycle ([ISO, 2015](#); [ISO 14040, 2021](#); [ISO 14044, 2021](#); [UNEP, 2011](#)). This final stage allows for a deeper validation of sustainability claims and supports a robust comparison with conventional solutions on the market.

2.2. Screening sustainability assessment (SSA) method

The Screening Sustainability Assessment (SSA) method consists of a structured questionnaire aimed at guiding the preliminary evaluation of products across three core SSbD aspects: i) Functionality; ii) Safety; and iii) Sustainability.

The development of the questionnaire followed an iterative process involving different groups of stakeholders depending on the aspect under evaluation. Overall, the development process involved seven partner institutions, including research institutes and product developers, represented by 17 experts. These partners collaborated with 11 end-user organizations such as museums, and cultural heritage institutions, together with curators and conservators, to integrate both technical and practical perspectives.

The functionality dimension was defined in co-creation with end users, ensuring that practical needs and conservation requirements were adequately captured. The safety dimension resulted from a longer process in which partner institutions were actively engaged, testing different approaches until the framework proposed here was consolidated. The sustainability dimension was developed by building on the European regulatory context and collecting targeted feedback from product manufacturers. Through this iterative exchange, which included surveys and dedicated meetings, the SSA tool was progressively refined before being applied to multiple case studies, as described in the following section.

This screening-level assessment is conceived as a pre-LCA step, supporting early-stage evaluation when detailed life cycle data are not yet available. A more comprehensive life cycle sustainability assessment (LCSA) can follow in subsequent development stages to provide a deeper understanding of the environmental, social and economic implications identified during the screening phase ([Kloepffer, 2008](#)).

As illustrated in [Fig. 1](#), the 3 abovementioned aspects are assessed across the entire life cycle of innovative and benchmark products.

The life cycle stages considered are: Raw materials; Production; Use – application; Use – post application; End of life.

These stages were selected based on the specific context of cultural heritage conservation and restoration. In particular, the distinction between the application and post-application phases within the use stage is crucial, as it reflects the different exposure scenarios, material behavior, and environmental implications inherent to conservation practices ([Semenzin et al., 2019](#)).

A set of criteria, defined through measurable indicators, is applied to

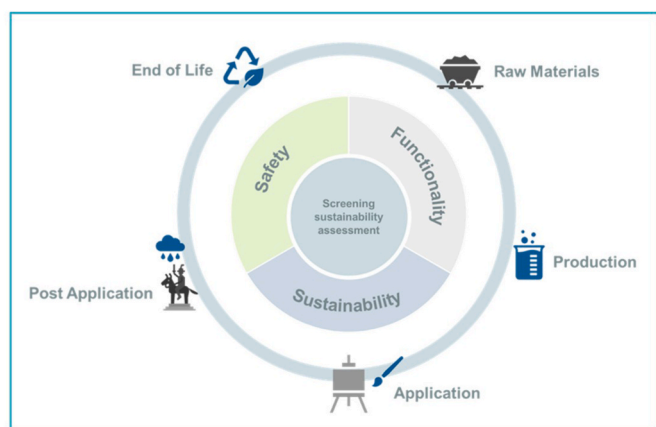


Fig. 1. Overview of the aspects and life cycle stages considered in the Screening Sustainability Assessment (SSA) method.

evaluate each aspect of SSbD performance. Criteria help in determining the significance and impact of each aspect within the life cycle stages. Finally, the assessment incorporates targeted questions designed to evaluate compliance with the established criteria. Each question has five possible answers that represent the level of satisfaction with a specific product solution, from "excellent" to "bad." Scores are assigned as follows: 5 for "excellent," 4 for "good," 3 for "moderate," 2 for "poor," and 1 for "bad." These scores are then averaged to visualize the overall results for both the different life cycle stages and functionality, safety and sustainability aspects.

2.2.1. Functionality

Functionality is defined as the ability of a product to be useful and to achieve the goal for which it was designed (Tavernaro et al., 2021).

Functionality is a crucial aspect of the SSA, aligning with the principle that the effectiveness of chemicals and materials should be evaluated in the context of their final use (Pizzol et al., 2023).

The evaluation of the Functionality aspect focused on key attributes including effectiveness, versatility, performance, and feasibility. The formulation of the assessment criteria was inspired by methodological insights from the H2020 NanoRestArt project (GA No. 646063) and was significantly strengthened by the involvement of several GREENART partners and stakeholders with complementary expertise. This included conservators as end users of the products, scientists with backgrounds in chemistry, materials science, and environmental science, as well as material producers and technology developers.

As a result, the assessment reflects a multi-perspective approach that captures the practical requirements, scientific validation needs, and production-related constraints associated with the development, implementation, and use of the target solutions.

2.2.2. Sustainability

Guided by regulatory drivers such as the Ecodesign for Sustainable Products Regulation (ESPR) (EC, 2024) and informed by expert contributions from the GREENART consortium, the sustainability aspect in this study was structured around three foundational pillars of sustainability: environmental, economic, and social. These pillars have been fully integrated into the SSA, ensuring a comprehensive evaluation that captures the full spectrum of impacts associated with GREENART products throughout their entire life cycle.

For the **environmental sustainability** pillar, factors such as the local supply chain, bio-based content, recycled content, water and energy consumption, and waste generation were considered.

In terms of **economic sustainability**, aspects such as diversified suppliers, estimated cost *per* unit, market size, time to market, and regulatory barriers were included.

For **social sustainability**, working conditions and the need for training were assessed.

2.2.3. Safety

The safety assessment in this study reflects the foundational principle of the SSbD Framework, which calls for the early identification and minimization of potential risks to human health and the environment throughout the product life cycle (Caldeira et al., 2022).

The assessment combines hazard and exposure classifications to provide a preliminary estimation of potential risks associated with each formulation.

Hazard Classification is performed in accordance with the Classification, Labelling and Packaging (CLP) Regulation (European Commission, 2008), which defines criteria for identifying Human health (H), Environmental (ENV), and Physical (P) hazards. In addition, the EC SSbD framework builds upon CLP criteria and introduces three additional hazard-based criteria: (H1) most harmful substances, (H2) substances of concern, and (H3) other hazard classes.

Exposure Classification follows a screening-level approach based on the ProScale method (ProScale, 2017), which estimates an Exposure Concentration Factor (ECF). The ECF quantifies the potential concentration of a target substance to which workers may be exposed, based on operational conditions. ECF values are derived from the ECETOC Targeted Risk Assessment (TRA) Tier 1 model (ECETOC, 2012), which provides default estimates for inhalation and dermal exposure. A logarithmic transformation is applied to standardize ECFs across exposure routes, aligning them with the scale of the hazard factor. Resulting values range from 10^{-5} (very low exposure) to 1 (high exposure).

The logarithmic transformation function is specifically tailored to each exposure route, with exposure ranges initially based on the ECETOC TRA tool for workers for inhalation and dermal routes (ProScale, 2017), as detailed in Table 1.

Risk Characterization is achieved by combining hazard and exposure information through a Control Banding Matrix approach (Zalk and Paik, 2016). This matrix enables a semi-quantitative classification of potential occupational risks, facilitating the early identification of risk hot-spots under limited-data conditions.

3. Results and discussion

This section presents and discusses the Screening Sustainability Assessment (SSA) method designed to evaluate the sustainability performance of product solutions across multiple dimensions, developed according to the methods described in section 2. As previously mentioned, the SSA method focuses on three key aspects: Functionality, Safety, and Sustainability. These are assessed across the entire product life cycle, which is segmented into five key stages: raw materials, production, use/application, use/post-application, and end-of-life. Each aspect is further detailed through a set of specific criteria, providing measurable indicators of sustainability performance. Finally, the questionnaire comprises a series of targeted questions designed to assess compliance with the SSA criteria, with five possible responses ranging from "excellent" to "bad." These responses are scored as follows: 5 for "excellent," 4 for "good," 3 for "moderate," 2 for "poor," and 1 for "bad." Table 2 outlines the criteria and related questions used to evaluate the screening-level sustainability performance across each assessed

Table 1

Range of modelled exposure for each exposure route (inhalative and dermal) according to the ProScale Method.

Route of exposure	Exposure concentration	
	Lowest value	Highest value
Inhalative (work exposure)	0.0001 mg/m ³	1000 mg/m ³
Dermal (work exposure)	0.03 mg/kg/day	141.43 mg/kg/day

Table 2
Screening Sustainability Assessment Method, assessing Functionality, Safety and Sustainability (Environmental (ENV), Social (S), Economic (E)) across five life-cycle stages.

Life Cycle Stages	Aspects	Criteria	Questions		
Raw Materials	Functionality	Effectiveness	How would you rate the effectiveness of the key ingredient in this product?		
		Sustainability	(ENV) Local supply chain	To what extent are you confident about the availability of local (EU) raw materials to support the production of the product?	
	(ENV) Bio-based content		To what extent is the product content biobased?		
	(ENV) Recycled/waste material content		To what extent is recycled or waste material content incorporated into the product?		
	(S) Working condition		How aware are you of the working conditions from which your raw materials are sourced?		
	(E) Diversified suppliers		How feasible is it to diversify your suppliers by sourcing from different countries?		
	Production		Functionality	Product versatility	How is product versatility optimized during production to suit diverse uses and applications?
			Sustainability	(ENV) Water consumption	How efficient is the production process in terms of water consumption?
	(ENV) Energy consumption			How efficient is the production process in terms of energy consumption?	
	(ENV) Waste generation	How efficient is the production process in terms of the generation of waste?			
(E) Estimated cost per unit	Which is the estimated economic cost (referred to the market price) to treat a square meter of work of art or to diagnose an art object?				
(E) Market size	How many potential customers (e.g. number of Museums or conservators worldwide) might be interested in this product?				
(E) Time to market	How much time is needed to have the product solution ready for the market?				
Use – application	Safety	Hazard of the ingredients	What is the hazard level of the most hazardous ingredient in this product?		
	Safety	Operational safety in the production phase	What is the safety level ensured for producers during the production process?		
Use – application	Functionality	Non-invasivity	What is the level of ability to detect signals of degradation with no need to remove material or by taking very small samples of material from the work of art?		
		Sensitivity	What is the level of ability to detect signals of degradation of different intensity?		
	Performance/Efficiency	How capable is the product solution of addressing its objective (e.g. cleaning, consolidation) in a reasonable application time (according to expert judgement)?			

Table 2 (continued)

Life Cycle Stages	Aspects	Criteria	Questions	
Use - post application	Sustainability	Applicability range	Is it possible to apply the product solution on different substrates?	
		Compatibility	How would you rate the chemical and physical compatibility of restoration materials with the original art materials, in relation to the nature of the substrate and their state of conservation, throughout the life cycle of new products?	
		Feasibility	Is there any specific technical challenge or barrier regarding the product up-scale?	
	Safety	(S) Need for training	Is specific training required for handling the developed product or system?	
		(E) Regulatory barriers	Are there any specific regulation/legislation that could slow down the process of the product solution entering the market?	
		Safety	Hazard of the mixture	What is the hazard level of the mixture?
	Operational safety in the use phase		What is the safety level ensured for users during the application phase?	
	End of Life	Functionality	Re-treatability	How feasible is to treat again the works of art while respecting the properties of the artefacts?
		Safety	Long-term impact on conservation	How well is the solution ensuring long-term action and limited changes over time of aesthetic/chemical/mechanical properties?
			Environmental Hazard	What is the hazard level ensured for the environment during the post-application phase?
End of Life	Sustainability	(ENV) Disposal instructions	Will you be able to provide clear and detailed disposal instructions for the product once it has reached the end of their lifecycle?	

aspect. The sustainability aspect is further detailed into three core dimensions: Environmental (ENV), Social (S), and Economic (E). The five-level response options associated with each question are provided in the Supporting Materials.

The core of the SSA method is a structured questionnaire consisting of 29 questions, designed to support a systematic and transparent assessment. Specifically, the questionnaire includes 10 questions addressing functionality, 14 focusing on sustainability, and 5 related to safety, the latter having been described in detail earlier in the manuscript.

3.1. Functionality aspect

Most of the functionality-related questions were derived from the experience gained in a previous project and were refined through expert input provided by project partners, ensuring their relevance to the context of restoration solutions for cultural heritage. Within the functionality aspect, two questions in the use phase—*non-invasivity* and *sensitivity*—are specifically applicable to diagnostic tools, as they address the ability to detect degradation without altering the artwork. Conversely, two questions in the post-application phase—*re-treatability* and *long-term impact on conservation*—are not applicable to diagnostic

tools, as they pertain to the performance and durability of active treatment products.

3.2. Sustainability aspect

The sustainability aspect comprises 14 questions addressing environmental, economic, and social aspects. The development of these criteria was informed by a combination of EU regulatory frameworks and strategic policy documents.

The **environmental dimension** is strongly aligned with the goals of the Ecodesign for Sustainable Products Regulation (ESPR) (EC, 2024) and the priorities set by the EU Circular Economy Action Plan (European Commission, 2020). It includes criteria related to the origin of raw materials with preference for EU-based supply chains (*local supply chain*), *bio-based content*, and the integration of *recycled or waste-derived materials*. The inclusion of bio-based content as a criterion also reflects the objectives of the European Bioeconomy Strategy (European Commission, 2018), which promotes the use of renewable biological resources to support a sustainable and circular economy. Additional questions address resource efficiency during production, focusing on *water consumption*, *energy consumption*, and *waste generation*. These aspects are consistent with the impact categories used in Life Cycle Assessment (LCA) (ISO 14040, 2021; ISO 14044, 2021) and are designed to support coherence between qualitative screening and downstream quantitative evaluations. Supplier diversification is consistent with the EU's goal of improving strategic resilience in supply chains, as supported by the JRC's Raw Materials Information System (RMIS).

The **economic dimension** includes indicators such as the estimated *cost per unit*, the potential *market size* (e.g., number of potential end users or institutions), and the *time-to-market* for the product. These criteria were initially developed within the NanoRestArt project. In addition, a specific question was included to capture *regulatory barriers* that may hinder the product's introduction to the market, reflecting the importance of anticipating legal or procedural constraints during early development stages.

The **social dimension** of sustainability is addressed through two questions. The first concerns *working conditions* along the raw material supply chain, which aligns with the United Nation Guiding Principles on Business and Human Rights (UN, 2011), as well as with recent developments such as the EU Corporate Sustainability Due Diligence Directive (CSDDD) (EU, 2024), which establishes obligations for companies to identify, prevent, and mitigate adverse human rights and environmental impacts across their value chains. The second focuses on the *need for training* to safely and effectively handle the developed solution. Although limited in number, the inclusion of two social criteria constitutes an initial effort to incorporate social responsibility within the SSA method, thereby enhancing its multidimensional scope alongside environmental and economic dimensions.

3.3. Safety aspect

The Safety aspect is evaluated across production, application and post-application stages of the life cycle, where potential human health and environmental risks are more readily identified through a screening-level assessment.

While the Functionality and Sustainability aspects are self-assessed by the product developers through the SSA Questionnaire, the Safety aspect is assessed by the team of experts responsible for the SSbD assessment.

The Safety aspect is evaluated by combining hazard and exposure classifications, enabling a preliminary estimation of potential risks associated with each formulation.

The **Hazard Classification** entails evaluating all ingredients used in the innovative formulations to investigate their intrinsic properties before further safety assessments. The primary objective of this step is to categorize chemicals, facilitating the elimination of highly hazardous

substances, promoting substitution or redesign, and minimizing the presence of substances of concern in innovative products.

The assessment proceeds in two steps: first, by evaluating the intrinsic hazard properties of all ingredients used in the innovative formulations, and second, by classifying the formulations according to the CLP regulation for mixtures (European Commission, 2008; Kienzler et al., 2014).

Additionally, the most promising ingredients and formulations are classified according to Step 1 of the SSbD framework (Caldeira et al., 2022).

The **Exposure Classification** is designed to assess occupational exposure to chemicals during the production and use phases of the innovative products. In order to support decision-making during the early design phase - when quantitative exposure data are often unavailable - a semi-quantitative screening approach is adopted. The evaluation relies on a control banding matrix, informed by a set of guiding questions developed to collect relevant information on potential exposure scenarios (Zalk and Paik, 2016). The questionnaire aims to gather general information on the product or product family, including details on production and application steps, as well as any Risk Management Measures (RMMs) currently in place. It also collects information on the physico-chemical properties of the product or product family, enabling a more informed and context-specific assessment.

Exposure classification is performed using the ProScale method, which builds on ECETOC TRA Tier 1 to estimate potential worker exposure via inhalation and dermal contact. The resulting ECFs reflect the relative exposure potential during production and application (ECETOC, 2012; ProScale, 2017).

Inhalation exposure is estimated by taking into account several key parameters. These include the standardized Process Categories (PROCs) as defined under the REACH regulation (European Commission, 2006), the intended use setting (industrial or professional), and the physical state of the substance (solid or volatile). The presence or absence of RMMs was also considered. In addition, the fugacity of the substance was evaluated and classified as negligible, low, medium, or high, based on vapour pressure data for volatile substances and dustiness levels for solids, as defined in the ECETOC method. For mixtures, a Concentration-Based Exposure Modifier was applied to further refine the exposure estimation (ECETOC, 2012).

Dermal contact exposure is assessed using the same framework, taking into consideration the applicable Process Categories and use setting. As with inhalation exposure, the Concentration-Based Exposure Modifier was applied for mixtures (ECETOC, 2012). In the specific context of this study, two relevant PROC categories were identified. PROC5 was selected for the production phase, which corresponds to "*Mixing or blending in batch processes for the formulation of preparations and articles*" and PROC10 was chosen for the use phase (application), which corresponds to "*Roller application or brushing*".

ECFs are derived from modelled exposure concentrations following the ProScale method.

As an example, Tables 3 and 4 show the exposure classification for both production and use phases for a product consisting of three hypothetical ingredients. The classification is carried out for the two exposure routes, Inhalation (I) and Dermal (D), first for individual ingredients, and then for the entire mixture during the use phase. The ECF values obtained for each ingredient are subsequently summed in order to calculate the ECF Inhalation and ECF Dermal values for the mixture.

According to the SSbD hazard classification (Step 1), four hazard levels have been identified, from "Level 0" to "Level 3". Level 0 (red) applies to chemicals that do not meet the SSbD H1 criterion and should be prioritized for substitution or re-design. Level 1 (orange) is for chemicals that meet SSbD H1 but not SSbD H2, with recommendations for substitution or redesign to minimize adverse effects. Level 2 (yellow) includes chemicals that meet SSbD H1 and SSbD H2 but not SSbD H3, requiring review and safe use management. Level 3 (green) covers chemicals that are not classified for the hazard classes currently

Table 3

Example of exposure classification during the production phase according to the ProScale approach and ECETOC TRA (EP: Exposure Prediction, ECF: Exposure Concentration Factor).

Production phase Ingredients	SSbD Hazard Classification	PROC (I,D)	Use (I,D)	Physical state (I)	RMM (I)	Vapour pressure (kPa) (I)	Fugacity (I)	EP Inhalation (mg/m ³)	EP Dermal (mg/kg/ day)	ECF inhalation	ECF Dermal
A	1	PROC5	Industrial	Liquid	Yes	0.87	Low	0.5	1.37	3.8E-03	5.9E-03
B	2	PROC5	Industrial	Liquid	Yes	3.75	High	25	1.37	2.1E-02	5.9E-03
C	3	PROC5	Industrial	Liquid	Yes	4E-37	Negligible	Negligible	1.37	Negligible	5.9E-03

considered, while recognising that adverse effects may still occur in specific applications depending on exposure conditions.

In the GREENART Control Banding Matrix, Safety is evaluated using a combined scoring system, which includes a numerical scale from 1 to 5 and an associated color code. This color code ranges from dark green, representing level 5 (i.e., an excellent level of safety), to red, representing level 1 (i.e., a bad level of safety).

Specifically, **Level 1** (Red) represents a bad level of chemical safety and requires immediate action. It corresponds to situation where the hazard is at its highest (Hazard Level 0) and represents a cut-off point where any level of exposure results in a score of 1, except for the lowest exposure range (1E-05 to 1E-04). **Level 2** (Orange) indicates scarce or poor level of safety. This level is typically assigned when there is a hazard level 1 coupled with an intermediate (from 1E-03) to high exposure level (up to 1E+00). While the risks are not as critical as Level 1, they still necessitate precautionary measures to mitigate potential harm. **Level 3** (Yellow) denotes moderate level of chemical safety. It usually arises from a medium hazard level combined with a moderate exposure situation. Although the risk is not as severe as in Levels 1 or 2, it still requires monitoring and appropriate safety measures to prevent potential harm. **Level 4** (Light Green) reflects a good or very good level of chemical safety. Hazard Level 3 generally receives a score of 5, except at the highest exposure level (1E-01 to 1E+01), where the score is reduced to 4. Finally, **Level 5** (Dark Green) corresponds to an excellent level of chemical safety, indicating not significant risk under normal conditions.

The matrix can be used for evaluating occupational risk both during the production stage, which involves exposure to the ingredients, and during the use/application phase, which involves exposure to the final product (i.e., mixture).

Fig. 3 illustrates an example of occupational risk classification during the production stage. During the production stage, each individual ingredient in a mixture is assessed separately for its hazard potential and exposure level. In this matrix, ingredients A, B, and C are evaluated by combining their hazard and exposure classifications. The final safety classification is determined by the worst-case scenario to ensure a conservative safety assessment.

In this specific example, the safety level is dictated by the inhalation risk of ingredient "B", which presents a hazard level of 2 and an exposure level between 1E-02 and 1E-01. This combination results in a safety level of 3, indicating a moderate level of safety.

Next, for the use stage, the focus shifts to the classification of the mixture as a whole. The safety classification considers how the combined properties of the ingredients could lead to exposure through inhalation or dermal contact. When multiple safety classifications are obtained—such as for both inhalation and dermal routes—the worst-case scenario is prioritized, leading to a conservative risk evaluation.

Fig. 4 presents an example of a safety classification for a product during its use stage. The matrix combines hazard classification and exposure levels to assess the overall safety. In this specific case, the product has a hazard classification of level 3 and an exposure level ranging between 1E-02 and 1E-01. This combination results in a safety level of 5, which corresponds to an excellent safety rating.

For the environmental dimension, the assessment focuses exclusively on hazard. This approach was adopted due to the current lack of reliable

data on potential environmental exposure, particularly in relation to emissions during manufacturing and use. Additionally, most of the evaluated products are presently produced and applied indoors, under controlled conditions, where the likelihood of release into the environment is considered minimal. Given these constraints and contextual factors, a hazard-only assessment was deemed appropriate as a first screening step to identify substances of potential environmental concern. The evaluation therefore concentrated on the intrinsic hazardous properties of the substances, independent of exposure scenarios. In Table 5 the Environmental Hazard Classification is presented. This classification is based on STEP 1 of the SSbD Framework, to which a class for score 4 (good) was added, corresponding to chronic and/or acute toxicity category 4 according to CLP classification (European Commission, 2008).

3.4. Demonstration of the screening sustainability assessment (SSA) method on protective coatings for cultural heritage

The questionnaire was distributed to relevant stakeholders, including product manufacturers and end users, who were asked to respond to the questions related to functionality and sustainability aspects. These results were then complemented by the Safety assessment, as described in the methodology outlined in Section 3.3. Once the responses to all questions related to the SSA questionnaire criteria are collected, the graphical representation of the results is automatically generated, providing a clear overview of performance across the different criteria, life cycle stages, and sustainability aspects. In total, the SSA tool was tested to 11 case studies, covering 25 innovative products and 9 benchmark solutions. For the purposes of this study, one illustrative case study is reported to demonstrate the practical application of the SSA method.

For the specific case study, the evaluation of the innovative products was performed jointly by five experts from the research institute developing the coatings, who discussed the questions and provided a consolidated response. The assessment also involved two additional experts from another research institution for the benchmark, in order to compensate for some missing information.

Two innovative protective bio-based coatings - referred to as Innovative 1 and Innovative 2 - developed within the HEU GREENART project were evaluated and compared against a conventional fossil-based benchmark. These coatings are designed to provide long-term protection to cultural heritage surfaces, acting as barriers against pollutants, humidity, and other degradation or corrosion agents. The innovative coatings incorporate both active and passive protection mechanisms, including multilayered and composite systems, formulated with bio-based monomers and polymers derived from renewable resources and natural waste, primarily sourced from the agri-food industry. Both Innovative 1 and Innovative 2 are nanocellulose- and nanolignin-based coatings, differing primarily in the solvent system: Innovative 1 is water-based, whereas Innovative 2 employs non-toxic, less hydrophilic solvents as alternatives to water. The selected benchmark represents a widely used methacrylate-based coating system that, despite its transparency and established performance, presents limitations in terms of removability, long-term stability, and sustainability performance. Although overall Safety scores are reported, detailed

Table 4
Example of exposure classification during the use phase according to the ProScale approach and ECETOC TRA (IEP: Ingredient Exposure Prediction, MEP: Mixture Exposure Prediction, IECF: Ingredient Exposure Concentration Factor, MECF: Mixture Exposure Concentration Factor).

Use phase Ingredients	% w/w	Hazard Classification	PROC (I, D)	Use (I, D)	Physical state (I)	RMM (I)	Vapour pressure (kPa) (I)	Fugacity (I)	IEP, Inhalation (mg/m3)	IEP, Dermal (mg/kg/day)	Percentage of substance in preparation (I, D)	Exposure modifying factor (I, D)	MEP, Inhalation (mg/m3)	MEP, Dermal (mg/kg/day)	IECF, inhalation	IECF, dermal	MECF, inhalation	MECF, dermal
A	0.5% ≤ % ≤ 1	3	PROCl0	Professional	Liquid	Yes	0.87	Low	0.5	27.43	<1 %	0.1	0.05	2.74	1.4E-03	8.0E-03	1.3E-02	3.6E-02
B	5% ≤ % ≤ 10		PROCl0	Professional	Liquid	Yes	3.75	High	10	27.43	5–25 %	0.6	6	16.46	1.1E-02	1.7E-02		
C	3% ≤ % ≤ 5		PROCl0	Professional	Liquid	Yes	3.81E-37	Negligible	Negligible	27.43	1–5 %	0.2	Negligible	5.49	Negligible	1.1E-02		

These results are then combined with the hazard classification within a control banding matrix (called GREENART Control Banding Matrix, Fig. 2), to classify the overall risk in both production and use phases.

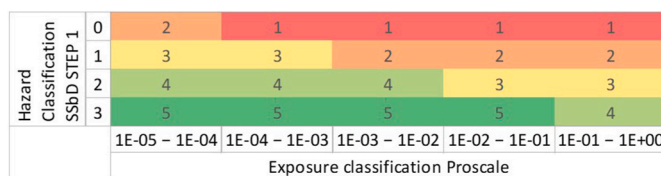


Fig. 2. Greenart control banding matrix.

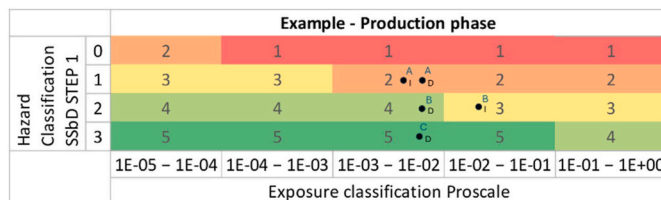


Fig. 3. Example of GREENART Control Banding Matrix results for Operational Safety during the production stage (A, B, and C represent the ingredients, while I and D indicate the Inhalation and Dermal exposure routes, respectively).

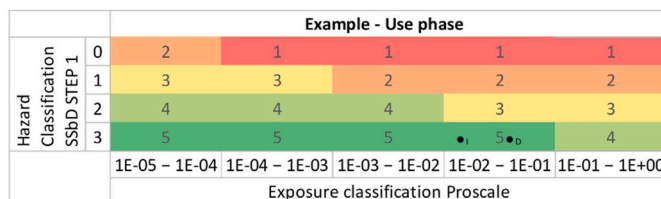


Fig. 4. Example of GREENART Control Banding Matrix results for Operational Safety during the use phase (I and D indicate the Inhalation and Dermal exposure routes, respectively, for the two mixtures).

Table 5
Environmental hazard classification.

Score	Environmental Hazards (CLP)	SSbD STEP 1
1	Persistent, bioaccumulative and toxic/very persistent and very bioaccumulative (PBT/vPvB) Persistent, mobile and toxic/very persistent and mobile (PMT/vPvM)	Level 0
2	Endocrine disruption Cat. 1 (environment) Hazardous for the ozone layer Chronic environmental toxicity (chronic aquatic toxicity) cat 1-3	Level 1
3	Endocrine disruption Cat. 2 (environment) Acute environmental toxicity (acute aquatic toxicity) cat 1-3	Level 2
4	Acute environmental toxicity (acute aquatic toxicity) cat 4	Level 2
5	No Environmental Hazard	Level 3

results are not disclosed due to confidentiality requirements regarding the specific composition of the innovative products, as defined in the project’s disclosure agreement. The SSA results are presented in radar charts to clearly display how each solution performs against the proposed criteria, allowing for a direct comparison of the different alternatives under study.

Fig. 5 illustrates the performance scores at the level of individual criteria, covering all assessed aspects and life cycle stages. This visualization enables a direct comparison of strengths and weaknesses across the different dimensions of the SSA, offering a detailed insight into the relative SSbD performance of each product alternative. Although these results are provided as an illustrative example, they reflect a common pattern observed in several case studies: the benchmark product generally exhibits lower performance in many safety and sustainability criteria when compared to the innovative formulations.

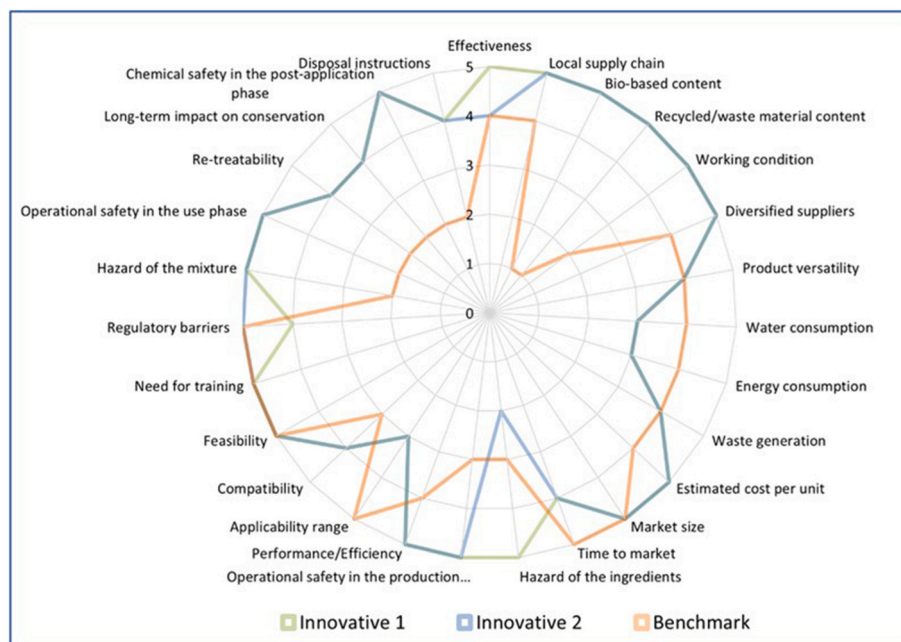


Fig. 5. Graphical visualization of the SSA at criteria level. Innovative 1 is shown in green, Innovative 2 in blue, and the benchmark in orange.

For instance, clear differences emerge across several safety-related criteria, including the *hazard of the mixtures*, the level of *operational safety during the application phase*, and *chemical safety in the post-application phase*, where the innovative products consistently outperform the benchmark. Similar trends can also be observed in selected sustainability aspects, such as the use of *recycled or waste material content* and *bio-based content*. Conversely, for criteria such as *water* and *energy consumption* during production, the innovative products are expected to show lower sustainability performance compared to the benchmark. These results reflect the assumption that bio-based resources, particularly at early stages of development, may require significant amounts of water and energy for their extraction and processing. This is partly due to the low TRL of current production, which is often limited to laboratory or pilot scale, where processes have not yet been optimized. A full Life Cycle Assessment (LCA) would be needed to confirm or revise these preliminary expectations (as foreseen in the third stage of the GREEN-ART approach).

Similarly, the benchmark still performs comparably or even better in some functionality-related criteria, particularly in terms of *applicability range*.

This highlights the importance of a multidimensional evaluation, where potential trade-offs between sustainability and functionality performance can be systematically identified and addressed. Moreover, this type of visualization supports the identification of potential hotspots in the performance of innovative products, highlighting specific criteria or life cycle stages where improvements may be needed. Notably, the structure of the SSA and the formulation of its targeted questions serve not only as a basis for systematic evaluation, but also as a means to foster awareness among stakeholders by drawing attention to sustainability aspects that are often neglected in conventional product development approaches.

Furthermore, to support the comparative analysis of different product solutions, the results of the SSA can be employed to highlight variations across the different life cycle stages as well as within each SSA aspect considered. To this end, a simplified scoring system is adopted: for each product, an overall score ranging from 1 (low performance) to 5 (high performance) is calculated. This score represents the average of the values assigned to the individual criteria, both at the level of life cycle stages and SSA aspects. The outcomes of this scoring approach

are visually represented in Fig. 6 (charts a and b), offering an intuitive overview of the relative performance of the assessed solutions.

These visual representations offer valuable insights into the distribution of performance across both life cycle stages (a) and SSA aspects (b). By aggregating the scores at these two levels, it becomes possible to identify which stages of the life cycle may be more critical from a holistic perspective, and which aspects (Functionality, Safety, or Sustainability) drive the overall performance of each product.

For this specific case study Fig. 6a shows variations among the assessed solutions across different life cycle stages. Notably, the highest scores for both Innovative 1 and Innovative 2 are observed in the raw materials and use phases, particularly in the post-application phase, where they outperform the benchmark by a wide margin (4.33 vs. 2.00). This reflects the favorable intrinsic properties of the bio-based ingredients and their reduced impact in the operational context. In contrast, the production stage shows more balanced results, with Innovative 1 scoring slightly higher (4.22) and Innovative 2 slightly lower than the benchmark (4.00). This suggests that potential sustainability benefits in manufacturing are not yet fully realized, likely due to the low Technology Readiness Level (TRL) and non-optimized production processes. These findings support the identification of production and end-of-life as critical stages where further improvements could be targeted.

Similarly, Fig. 6b provides a comparative overview of the three alternatives across the SSA aspect. The two innovative coatings demonstrate an overall higher performance than the benchmark across all aspects, with particularly notable differences in Safety. The Innovative 1 achieves the highest Safety score (5.00), followed by Innovative 2 (4.40), while the benchmark demonstrates a much lower performance (2.40), reflecting a more hazardous composition and less positive safety profile. In terms of Sustainability, the two innovative solutions perform similarly (4.43 and 4.50), both exceeding the benchmark (3.57), highlighting the potential of bio-based alternatives to contribute to improved environmental and socio-economic outcomes. Although the benchmark performs slightly lower in Functionality (3.63) compared to the innovative solutions (4.25 and 4.13), the differences are less pronounced, suggesting that trade-offs may still exist in specific functional criteria which require further optimization in future product development.

Although based on a single case study, these results demonstrate the practical value of the SSA method in identifying critical areas for

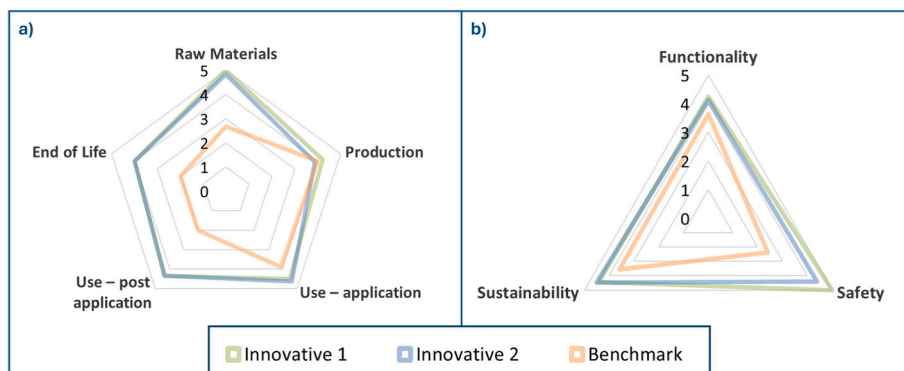


Fig. 6. Graphical visualization of the SSA at Life Cycle Stages (a) and SSA Aspects (b) levels. Innovative 1 is shown in green, Innovative 2 in blue, and the benchmark in orange.

improvement and in raising awareness of sustainability-related challenges that may otherwise remain unaddressed in early development phases.

4. Conclusions

This work presents the development and application of the Screening Sustainability Assessment (SSA) method, designed within the scope of the GREENART project, which aims to develop safe and sustainable solutions for the preventive conservation and restoration of cultural heritage. The proposed method enables a simplified yet structured evaluation of product alternatives, by assessing their performance across different life cycle stages and sustainability aspects, namely Functionality, Safety, and Sustainability. A simplified, illustrative comparison of two innovative protective coatings with a market benchmark was carried out to demonstrate how the framework can reveal critical sustainability trade-offs and guide improvement strategies.

The SSA serves as a preliminary screening tool, particularly valuable in the design and re-design phases of product development, when early-stage decisions must be made and full LCA cannot yet be performed due to limited data availability. Notably, it also captures socio-economic aspects that are frequently neglected in early development phases, largely due to the absence of practical screening tools that can accommodate such dimensions at low data resolution (Stoycheva et al., 2022). By combining semi-quantitative scoring with targeted sustainability-related questions, the method supports informed discussions among stakeholders and facilitates the integration of SSbD objectives from the earliest stages of development. Its application to solutions for cultural heritage restoration and preventive conservation illustrates its potential for promoting both technical performance and sustainability awareness in complex and traditionally under-assessed sectors. A key feature of the SSA method is its capacity for continuous updating, which allows it to remain responsive to evolving EU regulatory requirements and aligned with emerging policy priorities and market expectations. The need to operationalize the SSbD framework in practical, decision-relevant contexts has been increasingly recognised (Abbate et al., 2024; Garmendia-aguirre et al., 2025). In this regard, the SSA contributes as a structured and adaptable method that supports sustainability-oriented decision-making in data-limited, early-stage innovation contexts.

Nevertheless, the approach is not without limitations. The semi-quantitative nature of the assessment relies in part on expert judgment, which may introduce subjectivity. Future work will also consider possible discrepancies among stakeholder groups, as differences in perspectives and priorities may represent both a valuable source of insight and a potential source of bias. Addressing these aspects through uncertainty and sensitivity analyses will be a focus of future developments.

In addition, although the SSA was designed to offer a realistic and accessible set of criteria for project partners, future developments could enhance the method by further integrating social sustainability aspects and by strengthening the coverage of later life cycle stages — in particular, the end-of-life stage, which is currently addressed only through a single question related to environmental sustainability. Furthermore, the decision to adopt five broad life-cycle stages was a deliberate simplification aimed at ensuring feasibility under conditions of limited data availability; however, such a simplification inevitably limits the resolution of the assessment results. Increasing the number of stages, or introducing a more standardized distribution of questions across them, could provide a more detailed representation of product performance.

Future developments will focus on expanding the scope of the SSA, with the goal of generalizing the questionnaire to make it applicable beyond the field of art restoration and preventive conservation. Broadening the assessment criteria and terminology would facilitate its use in other sectors seeking to integrate sustainability and safety considerations into early-stage product development. This expansion will also require a broader involvement of stakeholders, in order to ensure that the adapted tool remains relevant, context-sensitive, and applicable across diverse innovation domains. In this perspective, the SSA is also intended to be applied to product groups highlighted as priorities within the ESPR Regulation, thereby further testing its scalability in different regulatory and industrial contexts.

CRediT authorship contribution statement

M. Menegaldo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **E. Giubilato:** Writing – review & editing, Validation, Supervision. **L. Pizzol:** Writing – review & editing, Supervision. **A. Zabeo:** Writing – review & editing, Supervision. **E. Badetti:** Writing – review & editing, Supervision. **E. Semenzin:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition.

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.

Acknowledgments

This work has received funding from the European Union#8217; s Horizon Europe Programme under Grant Agreement No. 101060941 (GREENART - GREen ENdeavor in Art ResToration).

The authors wish to thank Antonio Mirabile for his insightful contributions, and all GREENART project partners who supported the testing of the SSA method.

Special thanks are extended to AIRI (Italian Association for Industrial Research), in particular Andrea Porcari, for the valuable support provided during the development of preliminary concepts in the framework of the NANORESTART project Grant Agreement No. 646063 (NANO-RESTART - NANOMaterials for the REStoration of works of ART).

This work took place within the framework of the DoE 2023–2027 (MUR, AIS.DIP.ECCELLENZA2023_27.FF project).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cesys.2025.100381>.

Data availability

The data that has been used is confidential.

References

- Abbate, E., Garmendia Aguirre, I., Bracalente, G., Mancini, L., Tosches, D., Rasmussen, K., Bennett, M.J., Rauscher, H., Sala, S., 2024. Safe and Sustainable by Design Chemicals and Materials - Methodological Guidance.
- Abbate, Elisabetta, Ragas, Ad M.J., Caldeira, Carla, Posthuma, Leo, Garmendia Aguirre, Irantzu, Chloe Devic, Anne, Soeteman-Hernandez, Lya G., Huijbregts, Mark A.J., Sala, Serenella, 2025. Operationalization of the safe and sustainable by design framework for chemicals and materials: challenges and proposed actions. *Integrated Environ. Assess. Manag.* 21 (2), 245–262. <https://doi.org/10.1093/iteam/vjae031>.
- Apel, Christina, Kümmerer, Klaus, Sudheshwar, Akshat, Nowack, Bernd, Som, Claudia, Colin, Catherine, Walter, Lutz, Breukelaar, Johan, Meeus, Marcel, Ildefonso, Beatriz, Petrovykh, Dmitri, Elyahmadi, Chaima, Huttunen-Saarivirta, Elina, Dierckx, Ann, Devic, Anne Chloé, Valsami-Jones, Eva, Brennan, Maurice, Rocca, Cris, Scheper, Johanna, Strömberg, Emma, Soeteman-Hernández, Lya G., 2024. Safe-and-Sustainable-by-Design: state of the art approaches and lessons learned from value chain perspectives. *Curr. Opin. Green Sustainable Chem.* 45, 100876. <https://doi.org/10.1016/j.cogsc.2023.100876>.
- Arias, Ana, Cinelli, Marco, Moreira, Maria Teresa, Cucurachi, Stefano, 2024. A composite indicator for evaluating safety and sustainability by design and circularity in emerging technologies. *Sustain. Prod. Consum.* 51 (October), 385–403. <https://doi.org/10.1016/j.spc.2024.09.027>.
- Baglioni, Michele, Poggi, Giovanna, Chelazzi, David, Baglioni, Piero, 2021. Advanced materials in cultural heritage conservation. *Molecules* 26 (13). <https://doi.org/10.3390/molecules26133967>.
- Baglioni, Piero, Chelazzi, David, Giorgi, Rodorico, 2015. *Nanotechnologies in the Conservation of Cultural Heritage*. Dordrecht: Springer Netherlands.
- Balliana, Eleonora, Ricci, Giulia, Pesce, Cecilia, Zendri, Elisabetta, 2016. Assessing the value of green conservation for cultural heritage: positive and critical aspects of already available methodologies. *Int. J. Conserv. Sci.* 7 (SpecialIssue1), 185–202.
- Bennich, Therese, Belyazid, Salim, 2017. The route to sustainability-prospects and challenges of the bio-based economy. *Sustainability* 9 (6). <https://doi.org/10.3390/su9060887>.
- Brunelli, Andrea, Calgaro, Loris, Semenzin, Elena, Cazzagon, Virginia, Giubilato, Elisa, Marcomini, Antonio, Badetti, Elena, 2021. Leaching of nanoparticles from nano-enabled products for the protection of cultural heritage surfaces: a review. *Environ. Sci. Eur.* 33 (48). <https://doi.org/10.1186/s12302-021-00493-z>.
- Caldeira, C., Farcal, R., Moretti, C., Mancini, L., Rauscher, H., Rasmussen, K., Riego, J., Sala, S., 2022. Safe and sustainable chemicals by design chemicals and materials. Framework for the Definition of Criteria and Evaluation Procedure for Chemicals and Materials. <https://doi.org/10.2760/487955>.
- Caldeira, Carla, Farcal, Romeo, Garmendia Aguirre, Irantzu, Mancini, Lucia, Tosches, Davide, Amelio, Antonio, Rasmussen, Kirsten, Rauscher, Hubert, Sintes, Juan Riego, Sala, Serenella, 2022. *Safe and Sustainable by Design Chemicals and Materials - Framework for the Definition of Criteria and Evaluation Procedure for Chemicals and Materials*.
- Casini, Andrea, Chelazzi, David, Baglioni, Piero, 2023. Advanced methodologies for the cleaning of works of art. *Sci. China Technol. Sci.* 66 (8), 2162–2182. <https://doi.org/10.1007/s11431-022-2348-7>.
- EC, 2019. The European green deal. *European Commission* 53 (9), 24. <https://doi.org/10.1017/CBO9781107415324.004>.
- EC, 2021a. "pathway to a healthy planet for all. EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil. COM(2021) 400 Final 22. https://eur-lex.europa.eu/re-source.html?uri=cellar:a1c3456-b314-11eb-8aca-01aa75ed71a1.0001.02/DOC_1&format=PDF.
- EC, 2021b. The EU chemical strategy for sustainability towards a toxic-free environment. *European Commission* 39 (1), 9.
- EC, 2024. Regulation (EU) 2024/1781 of the European parliament and of the council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending directive (EU) 2020/1828 and regulation (EU) 2023/1542 and repeal. May):1–89. <http://data.europa.eu/eli/reg/2024/1781/oj>.
- ECETOC, 2012. ECETOC TRA version 3: background and rationale for the improvements. EUROPEAN CENTRE FOR ECOTOXICOLOGY AND TOXICOLOGY OF CHEMICALS. In: *European Centre for Ecotoxicology and Toxicology of Chemicals*, Brussels, Belgium.
- EU, 2024. Directive (EU) 2024/1760, of 13th June 2024: on corporate sustainability due diligence and amending directive (EU) 2019/1937 and regulation (EU) 2023/2859. *Off. J. Eur. Union* 1760 (3), 1–58. <http://data.europa.eu/eli/dir/2024/1619/oj>.
- European Commission, 2007. Communication from the commission to the council, the EUROPEAN parliament. THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A Lead Market Initiative for Europe.
- European Commission, 2008. Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on Classification, Labelling and Packaging of Substances and Mixtures, Amending and Repealing Directives 67/548/EEC and 1999/45/EC, and Amending Regulation (EC).
- European Commission, 2018. *A Sustainable Bioeconomy for Europe: Strengthening the Connection Between Economy, Society and the Environment*.
- European Commission, 2020. *A New Circular Economy Action Plan for a Cleaner and More Competitive Europe*, pp. 289–298.
- European Commission, 2022. COMMISSION RECOMMENDATION (EU) 2022/2510 of 8 December 2022 Establishing a European Assessment Framework for "Safe and Sustainable by Design" Chemicals and Materials, vol. 2531.
- European Parliament, and Council of the European Union, 2024. Regulation (EU) 2024/1781 of the European parliament and of the council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending directive (EU) 2020/1828 and regulation (EU) 2023/1542 and repeal. *Off. J. Eur. Union* (L 223), 1–42.
- Garmendia-aguirre, Irantzu, Rasmussen, Kirsten, Rauscher, Hubert, 2025. Safe and sustainable by design : driving innovation towards safer and more sustainable chemicals , materials , processes and products. *Sustainability & Circularity NOW*. <https://doi.org/10.1055/a-2636-1704>.
- ISO, 2015. EN 16760 Biobased Products – Life Cycle Assessment.
- ISO 14040, 2021. *Environmental Management - Life Cycle Assessment - Principles and Framework* ISO 14040:2021.
- ISO 14044, 2021. *Environmental Management - Life Cycle Assessment - Requirements and Guidelines* ISO 14044:2021.
- Kienzler, Aude, Berggren, Elisabet, Bessems, Jos, Bopp, Stephanie, Linden, Sander Van Der, Worth, Andrew, 2014. Assessment of Mixtures - Review of Regulatory Requirements and Guidance. EUR 26675. Publications Office of the European Union, Luxembourg. <https://doi.org/10.2788/138523>.
- Kloepffer, Walter, 2008. Life cycle sustainability assessment of products. *Int. J. Life Cycle Assess.* 13 (89), 95. <https://doi.org/10.1065/lca2008.02.376>.
- Lazzara, Giuseppe, Fakhruddin, Rawil F., 2019. *Nanotechnologies and Nanomaterials for Diagnostic, Conservation and Restoration of Cultural Heritage*. Elsevier.
- Pinheiro, Catarina, Beaumont, Anna, Cardinali, Francesca, Marra, Annalisa, Molinari, Daniela, Fife, Gwendoline, Wagner, Julia, Galacho, Cristina, Southwick, Caitlin, 2024. Access to sustainability in conservation-restoration practices. *Sustainability* 16 (17), 7675. <https://doi.org/10.3390/su16177675>.
- Pitaro, Fiorella, Seeger, Stefan, Nowack, Bernd, 2025. The safe and sustainable by design framework applied to graphene-based materials. *Environ. Int.* 197 (January), 109345. <https://doi.org/10.1016/j.envint.2025.109345>.
- Pizzolo, Lisa, Livieri, Arianna, Salieri, Beatrice, Farcal, Lucian, Soeteman-Hernández, Lya G., Rauscher, Hubert, Zabeo, Alex, Blossi, Magda, Costa, Anna Luisa, Peijnenburg, Willie, Stoycheva, Stella, Hunt, Neil, López-Tendero, María José, Salgado, Cástor, Reinoso, Julian J., Fernández, Jose F., Hristozov, Danail, 2023. Screening level approach to support companies in making safe and sustainable by design decisions at the early stages of innovation. *Cleaner Environmental Syst.* 10 (February). <https://doi.org/10.1016/j.cesys.2023.100132>.
- ProScale, 2017. *Proscale - a Life Cycle Oriented Method to Assess Toxicological Potentials of Product Systems*. Stockholm Sweden.
- Semenzin, E., Giubilato, E., Badetti, E., Picone, M., Volpi Ghirardini, A., Hristozov, D., Brunelli, A., Marcomini, A., 2019. Guiding the development of sustainable nano-enabled products for the conservation of works of art: proposal for a framework implementing the safe by design concept. *Environ. Sci. Pollut. Control Ser.* 26 (25), 26146–26158. <https://doi.org/10.1007/s11356-019-05819-2>.
- Stoycheva, Stella, Zabeo, Alex, Pizzolo, Lisa, Hristozov, Danail, 2022. Socio-economic life cycle-based framework for safe and sustainable design of engineered nanomaterials and nano-enabled products. *Sustainability* 14 (9). <https://doi.org/10.3390/su14095734>.
- Tavernaro, Isabella, Dekkers, Susan, Soeteman-Hernández, Lya G., Herbeck-Engel, Petra, Noorlander, Cornelle, Kraegeloh, Annette, 2021. Safe-by-Design part II: a strategy for balancing safety and functionality in the different stages of the innovation process. *NanoImpact* 24. <https://doi.org/10.1016/j.impact.2021.100354>.
- UN, 2011. *Guiding Principles on Business and Human Rights. Implementing the United Nations "Protect, Respect and Remedy" Framework*, New York and Geneva.
- UNEP, 2011. *Towards a Life Cycle Sustainability Assessment*.
- Zalk, David M., Paik, Samuel Y., 2016. *Risk Assessment Using Control Banding*, second ed. Elsevier Inc.