Green Chemistry

PAPER

View Article Online
View Journal

Check for updates

Cite this: DOI: 10.1039/d5gc06437f

Safe and sustainable by design: case study of a magnetic torus microreactor and bionanocompounds for wastewater treatment

Olga P. Fuentes,[a] Amaimen Guillén-Pacheco,[b,c] Johann F. Osma[d,e] and Guido Sonnemann *[a]

Received 30th November 2025,
Accepted 17th April 2026

DOI: 10.1039/d5gc06437f

rsc.li/greenchem

The Safe and Sustainable by Design (SSbD) framework provides a structured approach to integrate safety, environmental, social, and economic considerations into early-stage technological innovation. While SSbD has been applied to chemicals and nanomaterials, its implementation in wastewater treatment remains unexplored. This study represents the first application of SSbD to an emerging wastewater treatment technology involving a magnetic torus microreactor and magnetic nanoparticles (MNPs), aiming to generate a comprehensive understanding of its sustainability profile while advancing SSbD as a practical innovation tool. The assessment followed a five-step SSbD workflow: (1) hazard identification of raw materials, (2) evaluation of occupational risks during production, (3) integration of toxicological insights using zebrafish assays for MNP@laccase, (4) environmental impact assessment *via* life cycle assessment (LCA), and (5) exploratory evaluation of socio-economic aspects. Results showed that most raw materials achieved moderate SSbD scores, with tetramethylammonium hydroxide (TMAH) as the main safety hotspot. Substitution strategies improved environmental performance, and economic analysis confirmed strong feasibility. Social risks, particularly in the Colombian context, remain critical, highlighting the need for robust socio-economic indicators in early innovation stages. This work demonstrates how SSbD can guide wastewater treatment technologies toward safer, environmentally sustainable, and socially responsible solutions.

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Green foundation

1. This work advances green chemistry by applying the SSbD framework to an emerging wastewater treatment technology, integrating safety, environmental, social, and economic dimensions at an early innovation stage. It demonstrates how SSbD can guide material substitution, hotspot identification, and alignment of technological development with sustainability transitions.
2. The work identifies TMAH as a safety hotspot and proposes substitutions (sodium metasilicate for TMAH, PEEK for rivets), improving environmental performance and reducing safety risks. It provides the first SSbD application that incorporates social assessment, highlighting feasibility and relevance for holistic sustainability evaluation.
3. Greenness can be enhanced through quantitative social indicators, expanded life cycle assessments, and supply-risk considerations for critical raw materials, supporting equitable, resilient, and long-term sustainable deployment.

Introduction

The integration of the Safe and Sustainable by Design (SSbD) approach within the Chemicals Strategy for Sustainability (CSS) is a pivotal aspect of the European Green Deal's commitment to reducing negative impacts associated with chemicals.[1] This strategic framework is designed to address concerns related to human health and environmental sustainability throughout the life cycle of chemicals, materials, products, and services within the European Union (EU) market.[2] Specifically, the SSbD approach emerging from the CSS underscores the importance of not only meeting safety standards

[a]Univ. Bordeaux, CNRS, Bordeaux INP, ISM, UMR 5255, F-33400 Talence, France. E-mail: guido.sonnemann@u-bordeaux.fr
[b]Davinci – School of Basic Sciences, Technology, and Engineering (ECBIT), Electronic, Telecommunication, and Network Training Chain (ETR), Universidad Nacional Abierta y a Distancia (UNAD), Calle 14 Sur No. 14–23, 111711 Bogotá, DC, Colombia
[c]Laboratory of Neuroscience and Circadian Rhythms. School of Medicine, Universidad de Los Andes, Cra. 1E No. 19a-40, 111711 Bogotá, DC, Colombia
[d]Department of Electrical and Electronic Engineering, Universidad de Los Andes, Cra. 1E No. 19a-40, 111711 Bogotá, DC, Colombia
[e]Department of Biomedical Engineering, Universidad de Los Andes, Cra. 1E No. 19a-40, 111711 Bogotá, DC, Colombia

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

but also proactively considering and minimizing the environmental impact of technologies and solutions.[3] By adopting SSbD, the EU aims to ensure that the development and deployment of these innovations align with sustainability principles, contributing to a more resilient and environmentally friendly region.[4,5]

While SSbD and CSS initiatives originate in Europe, the challenges addressed by these frameworks are highly relevant in the Colombian context. Colombia faces increasing pressure on its water resources due to urban growth, industrial expansion, and agricultural activities, which contribute to the contamination of rivers, lakes, and aquifers with phenols, dyes, and other persistent pollutants.[6–8] Wastewater treatment has an important role in safeguarding public health and ecosystems, yet conventional technologies often rely on hazardous chemicals, energy-intensive processes, and infrastructure that may not align with long-term sustainability goals.[9,10] The urgent need to transition toward cleaner, safer, and more resource-efficient water treatment solutions makes wastewater treatment a key domain for applying and testing the SSbD framework.[11,12] Within this context, SSbD provides a structured methodology for evaluating technologies across safety, environmental, social, and economic dimensions, and for identifying opportunities to minimize unintended impacts from the outset of innovation.

Microreactor-based technologies have gained increasing attention in wastewater treatment due to their enhanced mass and heat transfer, high surface-to-volume ratios, and precise process control.[13,14] These systems have been successfully applied to the degradation of organic pollutants such as phenols, dyes, and pharmaceutical residues through catalytic, photocatalytic, and enzymatic processes.[15–17] Recent studies have demonstrated that microreactors can improve reaction efficiency, reduce reagent consumption, and enable process intensification compared to conventional batch systems.[18–21] Moreover, the integration of nanomaterials, including magnetic nanoparticles (MNPs), has further expanded their potential by facilitating catalyst recovery and reuse while enhancing catalytic activity.[22–24]

From a sustainability perspective, several studies have evaluated microreactor systems using conventional assessment tools, particularly life cycle assessment (LCA) and related metrics.[25–27] These studies generally highlight potential advantages such as reduced reagent consumption, lower waste generation, and improved energy efficiency due to process intensification. However, they also highlight the disadvantages associated with material use, fabrication complexity, and energy demands at small scales. Despite these insights, existing sustainability assessments of microreactors remain largely focused on environmental indicators and are typically conducted at later stages of technology development. As a result, they provide limited guidance for early-stage design decisions and often overlook critical aspects such as chemical safety, hazard profiles, and socio-economic considerations. In this context, the SSbD framework offers a more comprehensive and forward-looking approach by integrating safety, environmental, and socio-economic dimensions from the earliest stages of innovation.

The SSbD framework has been previously explored in studies addressing chemicals and materials, particularly within the context of European initiatives to promote safer and more sustainable innovation.[28–30] These applications have helped to refine the methodology and demonstrate its value in guiding early-stage design choices. However, to our knowledge, this is the first time the SSbD framework will be applied to wastewater treatment, and specifically to technologies involving nanocompounds. Extending SSbD into this field provides a novel case study that not only reveals the sustainability potential of wastewater innovations but also exposes methodological challenges in addressing complex, real-world systems.

This study applies the SSbD framework to an emerging technology for wastewater treatment based on a magnetic torus microreactor and MNPs.[22] In this system, the microreactor support enzyme-driven oxidation processes that break down phenols and dyes. To test how effectively the microreactor can transform dyes, laccase enzymes were chemically attached to magnetite nanoparticles. The technology was then tested with real wastewater by analyzing key water-quality indicators and assessing the removal of phenolic compounds and azo dyes.

In the initial phase of SSbD, step 1 focused on identifying the hazard properties of raw materials essential for microreactor fabrication and MNPs production. Step 2 involved assessing the risk and exposure associated with the production processes of both microreactors and MNPs, particularly concerning worker safety. Moreover, step 3 integrated insights from toxicological studies, particularly utilizing the zebrafish model, to evaluate the potential risks posed by MNPs@laccase. Moving to step 4, the environmental impacts were assessed utilizing LCA methodology, with a specific focus on the production stage. Finally, step 5 explored socio-economic aspects as an emerging dimension of SSbD, recognizing that while methodologies remain under development, forthcoming policies such as the Corporate Sustainability Reporting Directive (CSRD) are expected to strengthen these assessments.[3] Concurrently, Life Cycle Sustainability Assessment (LCSA) continues to mature, increasing its suitability for integration into SSbD evaluations.[31]

The aim of this work was to apply and test the SSbD framework on an emerging wastewater treatment technology to assess its safety and sustainability profile and demonstrate the framework's value as a tool for guiding innovation, providing critical insights and establishing a reference point for future innovation in environmental engineering, particularly in contexts such as Colombia, where sustainable water management remains an urgent national priority.

Methods

Description of the emerging technology

This case study addressed an emerging technology for wastewater treatment that includes a magnetic torus microreactor

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

and functionalized magnetite nanoparticles in order to assess their potential within the SSbD framework, see SI, Fig. S1.[22]

Magnetic bionanocomposites. The catalytic component of the system consists of magnetite nanoparticles (Fe_3O_4) and laccase-functionalized magnetite bionanocomposites (MNPs@laccase), which promote the degradation of organic contaminants in wastewater. Magnetite nanoparticles were selected due to their high surface area, chemical stability, and magnetic properties, which allow easy separation and recovery from treated water using an external magnetic field. The synthesis was carried out following the process reported in Peñaranda *et al.* study.[22]

To enhance catalytic performance, the magnetite nanoparticles were functionalized with the oxidative enzyme laccase, producing MNPs@laccase. Laccase is a multicopper oxidase enzyme capable of catalyzing the oxidation of a broad range of phenolic and aromatic compounds, including dyes and phenols, using molecular oxygen as the electron acceptor.

Microreactor system. Wastewater treatment experiments were carried out using a torus-shaped microreactor designed for continuous flow operation. The microreactor had a total internal volume of 150 μL and was operated under laminar flow conditions. Both artificial and real wastewater streams were introduced into the microreactor using a syringe pump at a constant flow rate of 12 mL h^{-1}. At this flow rate and considering the internal volume of the device, the residence time of the wastewater within the microreactor was approximately 45 s. All experiments were conducted at ambient temperature (≈25 °C).

Two types of artificial wastewater were prepared to evaluate the treatment performance of the system. First, Eriochrome Black T was used as a model dye pollutant. Dye solutions were prepared at concentrations of 5, 10, and 20 mg L^{-1} and adjusted to pH 5.5. These solutions were treated in the microreactor using either MNPs or MNPs@laccase. A second artificial wastewater model containing phenol was also prepared to evaluate phenolic compound degradation. Phenol solutions were prepared at 5, 10, and 20 mg L^{-1}, with the solution adjusted to pH 4.42 prior to treatment. Both artificial wastewater streams were processed under the same microreactor operating conditions described above.

To evaluate the system under realistic conditions, real wastewater samples were collected from the laboratories of the School of Medicine at Universidad de los Andes (Bogota, Colombia). The wastewater corresponded to high-pollution sewage conditions, characterized by elevated organic content. The composition of the collected wastewater included phenolic compounds and high biochemical oxygen demand (BOD). The main characteristics of the real wastewater are summarized in SI, Table S1. For real wastewater experiments, a total volume of 1 L was processed through a single microreactor under the same operating conditions.

The efficiency of the microreactor system was evaluated by measuring pollutant degradation after treatment. For artificial phenol-containing wastewater, degradation efficiencies ranged from 39 to 75% depending on the operating conditions and catalytic system used. In contrast, the phenol degradation in real wastewater reached approximately 18%. The lower performance was attributed to the high biochemical oxygen demand (BOD) of the real wastewater (385 mg L^{-1}), which reduced the availability of dissolved oxygen required for the laccase-catalyzed oxidation reactions, as laccase enzymes utilize molecular oxygen as a cofactor during catalytic cycles.

Implementation of the SSbD framework to the case study

The materials used in the technology were assessed across the corresponding steps of the framework. The production of MNPs involved the use of $FeCl_2$, $FeCl_3$, NaOH, and TMAH as raw materials. In parallel, the magnetic torus microreactor was fabricated using poly(methyl methacrylate) (PMMA) sheets, ethanol, rivets, and polyether ether ketone (PEEK) fittings.

Fig. 1 shows the sequential stages of the case study, detailing the life cycle from raw material acquisition for microreactor manufacturing, through the synthesis and functionali-

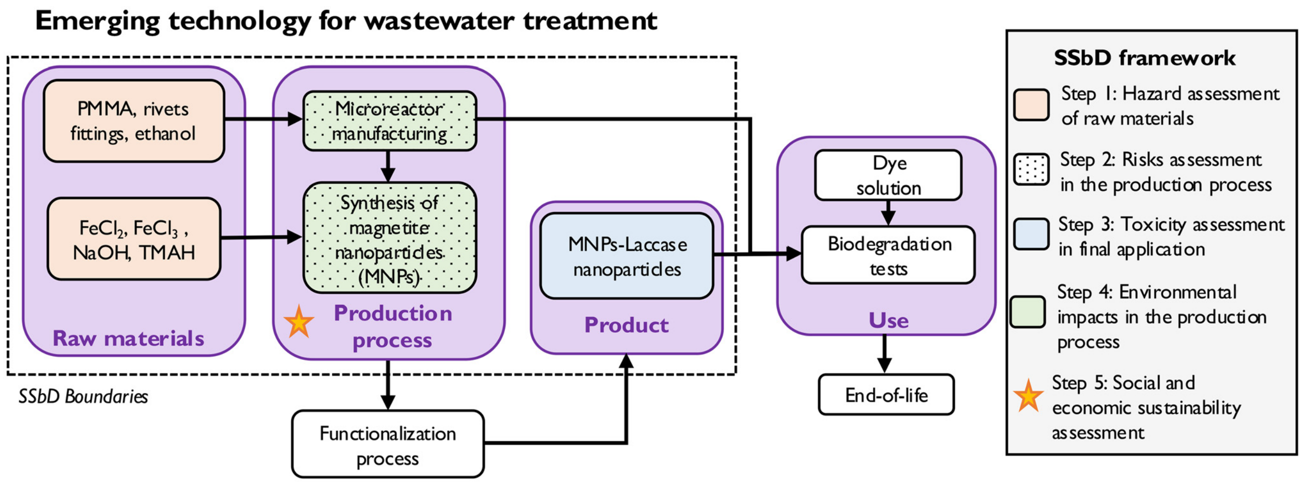

Fig. 1 Process flowchart of the case study and coverage of the SSbD framework steps.

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

zation of MNPs, to their application in wastewater treatment and eventual end-of-life management. Each stage is systematically mapped, with clear demarcation of system boundaries, distinguishing between processes assessed under the SSbD framework and those excluded from the assessment.

All steps proposed by the framework were applied, following the recommended procedures wherever possible. However, in cases where full implementation was not feasible, proxies were used in the assessment methods and scoring criteria. A detailed explanation of these modifications can be found in the SI.

Step 1 – Hazard assessment of raw materials. In this step, we conducted a comprehensive assessment of the hazard levels associated with the raw materials utilized at each stage of the emerging technology. Employing the SSbD approach, we examined the classification of chemicals according to the criteria outlined by the Classification, Labelling, and Packaging (CLP). This involved a detailed analysis of their physico-chemical properties, toxicological effects, and ecotoxicological impacts. Hazard profiles were collected from the European Chemicals Agency (ECHA) database, with proxies applied where necessary (see SI, Table S2).

Step 2 – Risk assessment in the production phase of microreactors and MNPs. This step focuses on the occupational safety and health assessment for workers The Chemical Safety Assessment and Reporting tool (Chesar v3.8) developed by ECHA, was used to perform a comprehensive risk assessment to workers in the production steps of the magnetic torus microreactor and MNPs.[32] Physico-chemical properties and environmental fate data for each raw material were compiled from the registered dossiers under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation (see SI, Table S11). This information was integrated into the Chesar tool, beside hazard data covering physico-chemical, environmental, worker, and consumer aspects (see SI, Table S12). Moreover, in this table were included values for Derived No-effect Levels for human health (DNEL) setting for workers and the Predicted No Effect Concentration (PNEC) for the environment which are useful for the hazard assessment.

Further refining the assessment, detailed use descriptions for each raw material were identified, ensuring a cohesive understanding of their application and conditions of use. Utilizing use maps, particularly the one developed by the European Solvents Industry Group (ESIG), offered a standardized framework for assessing exposure and risk across all raw materials.[33] Despite the absence of specific substance-related information, the general conditions of use and exposure scenarios were employed from the use map. The Generic Exposure Scenarios (GES) considered were manufacture, formulation, and on-site use, with the corresponding contributing scenarios (CSs) detailed in SI, Table S13.

Inhalation and dermal are the relevant exposure routes for workers. Therefore, human health and environmental exposure assessments were conducted using the Targeted Risk Assessment (TRA) Workers 3.0 and EUSES 2.1.2 datasets integrated into Chesar, yielding Risk Characterization Ratios (RCRs) for each raw material across different process categories (PROC) and environmental release concentration (ERC).

Step 3 – Toxicity assessment in the final application phase. In this step, the toxicity of functionalized nanoparticles (MNPs@Laccase) was evaluated to determine whether their use poses any potential risks to both consumers and the environment. The human health assessment was performed using findings from Guillén-Pacheco *et al.*'s study.[34] Zebrafish (*Danio rerio*) was selected as the animal model for this study, primarily due to their established physiological and genetic similarities to humans.[35–37] Zebrafish offer a robust and well-recognized platform for toxicity testing, providing valuable insights into the potential adverse effects of nanoparticles at various developmental stages.[38]

Wild-type TABS zebrafish were obtained from the Laboratory of Neuroscience and Circadian Rhythms, School of Medicine, Universidad de los Andes, Colombia. The procedures with animals were approved by the Institutional Animal Care and Use Committee of Universidad de los Andes (CICUAL from its name in Spanish) with the code C.FUA_19-004.

MNPs@Laccase nanoparticles were synthesized and evaluated following the OECD Guide for Fish Embryonic test with additional modifications for adult's fish analysis.[39] To determine the exposure of MNPs@Laccase on adult animals, six animals of 1.5 years of age per concentration (1 and 10 μg mL^{-1}) were placed in aquariums with 2 L of water and conditions optimal for the species. The animals were treated using a mixture of brine shrimp, MNPs@Laccase and flakes of Zeigler Aquatox® fish diet, presoaked for 5 min before being given as food. The treatment was applied for 5 days and then the animals were euthanized according to laboratory protocols for others analysis.[40] For the control group, untreated animals were used to maintain the optimal conditions for the species.

Finally, these findings were adapted to the SSbD framework in order to address the toxicology potential of MNPs used in the emerging technology. This integration of toxicology assessments within the SSbD framework provided valuable insights into the safety implications of the technology, contributing to a holistic understanding of its potential risks and benefits.

Step 4 – Environmental sustainability assessment. In this step, the environmental sustainability of the emerging technology was assessed in terms of environmental impacts in different stages of its life cycle. It was assessed through the application of the LCA methodology for the production of microreactors and MNPs at laboratory and industrial scales.[41] The LCA methodology uses the ISO 14040-44 standard and involves four steps: (1) goal and scope; (2) life cycle inventory; (3) environmental impact assessment; and (4) interpretation of results.[42] Following it, the goal and scope was defined as the evaluation of environmental effects associated with the production of MNPs using the microreactors adopting a cradle-to-gate approach. In this study, the industrial production of MNPs was considered to assess impacts related to manufactur-

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

ing and operation aspects. The primary goal was to identify the stages with the most significant environmental impact and propose measures for mitigation. Therefore, functional unit was established as 100 tons per year at the industrial scale.

In terms of the life cycle inventory, the data used were derived from the upscaling of the process outlined in Fuentes *et al.* study.[41] The inventory modeling was performed in OpenLCA® 1.11 software and background data were obtained from Ecoinvent 3.5 database. According to the SSbD framework, the study should incorporate impact categories associated with the Environmental Footprint (EF) method. The European Commission supports for the adoption of this approach for evaluating the environmental performance of products, positioning it as an essential standard in conducting LCA studies. However, the LCA results were conducted by the ReCiPe midpoint (H), and the 18 impact categories were organized into four primary clusters: toxicity, climate change, pollution, and resources, see SI, Fig. S3. Importantly, this convergence of impact categories implies that the results obtained from the LCA analysis conducted in this study can be seamlessly adapted to align with the requirements of the SSbD framework. This adaptation harmonizes with the main goal of SSbD, which is to promote the use of chemicals that contribute to advancing a "toxic-free environment". By incorporating these considerations into the LCA framework, the study actively contributes to the broader objective of implementing sustainable practices and minimizing environmental harm in chemical processes.

Step 5 – Social and economic sustainability assessment. The goal of the implementation of social life cycle assessment (S-LCA) in this work is to evaluate the social risks associated with the proposed emerging technology for wastewater treatment involving a magnetic torus microreactor and MNPs.

The functional unit for S-LCA was the same that LCA and it was set as the production of 100 ton per year of MNPs. The social inventory was modeled in Open LCA® 2.2 software, and background data for social aspects were sourced from PSILCA V3 – Worker Hours (Developer version). A cut-off criterion of $10 \times ^{-5}$ was applied for the definition of the product systems, according to the features of the used version of the PSILCA database.

The social assessment was conducted following the Social Impact Weighting Method, which different risks are characterized and expressed in medium-risk hours. Moreover, this method proposes the evaluation of 55 social indicators, which are structured according to the UNEP/SETAC guidelines.[43] This framework addresses a set of 23 impact subcategories classified into five stakeholders, namely, workers, value chain actors, local communities, society, and consumers. In this study, the selection of relevant categories of stakeholders and impacts subcategories was based on the social context of the country and "workers" was considered as a key stakeholder due to the significant impact they have on the production of MNPs.

Geographical location for the supply chain to produce MNPs was Colombia to allow a representative coverage of the associated impact subcategories considered. Table S26, in SI, summarizes the selected subcategories and their corresponding indicators considered in this study. Additionally, the social inventory implemented in PSILCA database is presented in SI, Table S27.

Results and discussion

Step 1 – Hazard assessment of raw materials

The data obtained from the ECHA database served as a resource to access information on the properties and hazards associated with each raw material, see SI (Table S1). Results revealed an understanding of the hazards of each raw material, encompassing various dimensions including physical, human health, and environmental risks, as well as factors such as flammability, reactivity, toxicity, and potential for environmental harm, see SI (Tables S3 to S5). These findings illustrate the classification of raw materials according to the CLP criteria for each assessed category, revealing that most raw materials are associated with one hazard category. Despite extensive research using the ECHA database, certain hazard classes remained without classification due to conflicting findings or a lack of available data. As shown in SI (Table S6), these cases require further justification, since an SSbD assessment cannot be completed while uncertainties persist in a substance's hazard profile.[1]

Then, the hazard profiles for raw materials were completed and the evaluation of the SSbD criteria was conducted, see SI (Tables S7 to S9). Based on this information, three criteria defined by the SSbD framework were evaluated, and scores were assigned accordingly (see SI, Table S10). Each substance received a score reflecting the level of hazard associated with the aspects addressed by each criterion. The first criterion (H1) prioritizes the most harmful substances for substitution or redesign to mitigate adverse effects. Chemicals failing this criterion are assigned a level 0. The second criterion (H2) addresses substances of concern, which exhibit hazardous properties but with a safety level. Chemicals failing this criterion are designated a level 1. The third criterion (H3) includes other hazard classes, integrating properties not covered by H1 and H2. Chemicals failing this criterion are assigned a level 2. Finally, chemicals meeting all safety criteria are designated a level 3.

The evaluation in Table 1 assesses raw materials based on the proposed SSbD criteria. Results indicate that most chemicals pass with a level 2 or 3. However, TMAH fails to meet the criteria due to its implications for specific target organ toxicity – repeated exposure (STOT-RE), indicating its status as one of the most harmful substances. Furthermore, TMAH, PMMA, and PEEK were classified as substances of concern due to their human health hazards related to specific target organ toxicity – single exposure (STOT-SE) and chronic aquatic toxicity in environmental hazards. Regarding the criterion of other hazard classes, many chemicals are involved due to

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Table 1 Evaluation of raw materials according to the criteria defined in SSbD for step 1

Criteria	Hazards	PMMA	Rivets	Ethanol	PEEK	NaOH	Iron(II)	Iron(III)	TMAH
Most harmful substances (criterion H1)	Human health	—	—	—	—	—	—	—	STOT-RE (Cat 1)
	Environment	—	—	—	—	—	—	—	—
	Physical	—	—	—	—	—	—	—	—
Substances of concern (criterion H2)	Human health	SS (Cat 1)	—	—	—	—	—	—	STOT-SE (Cat 1)
	Environment	—	—	—	AT(l-t) (Cat 2)	—	—	—	AT(l-t) (Cat 2)
	Physical	—	—	—	—	—	—	—	—
Other hazard classes (criterion H3)	Human health	SCI (Cat 2) STOT-SE (Cat 3)	—	SEDI (Cat 2)	ATO (Cat 4)	SCI (Cat 1A) SEDI (Cat 1)	ATO (Cat 4) SEDI (Cat 1)	ATO (Cat 4) SCI (Cat 2) SEDI (Cat 1)	ATO (Cat 2) ATD (Cat 1) SCI (Cat 1B) SEDI (Cat 1)
	Environment	—	—	—	—	—	—	—	—
	Physical	FL (Cat 2)	—	FL (Cat 2)	—	Corr. (Cat 1)	Corr. (Cat 1)	Corr. (Cat 1)	—
SSbD level		Passed criterion H1	Passed all criteria	Passed criteria H1 and H2	Passed criterion H1	Passed criteria H1 and H2	Passed criteria H1 and H2	Passed criteria H1 and H2	Fail the criteria
		1	3	2	1	2	2	2	0

SS: skin sensitisation; STOT-RE: specific target organ toxicity – repeated; STOT-SE: specific target organ toxicity – single; AT(l-t): aquatic toxicity (long-term); SCI: skin corrosion/irritation; SEDI: serious eye damage/eye irritation; ATO: acute toxicity – oral; ATD: acute toxicity – dermal; FL: flammable liquids; Corr.: corrosivity.

implications for acute toxicity, skin corrosion/irritation, and eye damage categories.

Based on our findings for step 1, it is evident that thorough consideration and mitigation strategies are necessary to address the identified hazards for ensuring the safety and sustainability of processes.

Step 2 – Risk assessment in the production phase of microreactors and MNPs

Findings from the risk assessment are summarized in SI, Tables S14 and S15. Results include the calculated RCRs for both environmental and human health considerations. The SSbD framework proposed the occupational safety and health (OSH) criteria to classify the calculated RCRs of both approaches human health and environment. The scoring details are provided in SI, Table S16. The first criterion (OSH1) considers if the total RCR >1 and more than one individual RCR >1, the material should be classified with score 0. The second criterion (OSH2) considers if total RCR >1 but at least 1 individual RCRs >1, the material is assigned a score of 1. The third criterion (OSH3) considers if total RCR >1 but all individual RCRs <1, the material is scored 2. Finally, if all RCRs ≤1 the material is assigned the highest score of 3.

This scoring system was systematically applied to each contributing scenario (CS), categorizing the stages of manufacturing, formulation, and on-site use according to their risk acceptability levels (see in SI, Tables S17 and S20). For occupational exposure, only long-term systemic inhalation and dermal exposure routes were considered, as they are the most relevant to this emerging technology.

Human health and environmental scores were then jointly evaluated to determine whether a raw material meets the SSbD risk acceptability threshold. The consolidated results of the risk assessment are presented in Table 2. A material is assigned an overall SSbD level of 3 only if it passes both the human health and environmental risk assessments. According to this evaluation, PMMA, ethanol, and PEEK were classified

Table 2 Overall SSbD classification for each raw material in step 2

	OSH scores			SSbD level
	Environment	Human health		
PMMA	0	3	→	1
Rivets	3	3		3
Ethanol	0	3		1
PEEK	0	3		1
NaOH	3	2		3
Iron(II)	3	3		3
Iron(III)	3	3		3
TMAH	0	0		0

SSbD Level	Safety
3	Negligible risk
2	Medium risk
1	High risk
0	Very high risk

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

with a SSbD level of 1. Notably, TMAH was identified as posing significant risks to both human health and the environment, indicating a clear need for targeted risk mitigation. Other materials showed negligible risk and were considered acceptable within the SSbD framework.

Step 3 – Toxicity assessment in the final application phase

In this phase, zebrafish were exposed to MNPs@Laccase nanoparticles through an indirect route *via* ingestion in their food. This exposure route reflects a plausible real-world scenario in which nanoparticles enter the food chain, raising concerns about their potential impact on health. The risk associated with ingestion is directly linked to the exposure level, *i.e.*, the amount consumed.

The study by Guillén-Pacheco *et al.* investigated nanoparticle accumulation in several tissues, including the brain, gills, gastrointestinal (GI) tract, and muscle.[34] For example, SI, Fig. S2, presents brain tissue concentrations for the control group (0.066 mg g^{-1}), fish exposed to MNPs@Laccase at 1 μg mL^{-1} (0.058 mg g^{-1}), and fish exposed at 10 μg mL^{-1} (0.068 mg g^{-1}). Interestingly, these values suggest that MNPs@Laccase do not exhibit a strong tendency to persist in brain tissue compared to unexposed controls. Therefore, if humans were exposed to comparable concentrations, the associated health risk would likely be minimal. However, long-term and more detailed toxicological studies remain essential to establish a comprehensive safety profile for bionanocomposites. These findings nonetheless provide useful insight into the safety characteristics of MNPs@Laccase.

Within the SSbD scoring framework for step 3, the final application phase considers both human health and environmental risk assessments. In this study, the human health assessment, based on the results above, passed the evaluation. However, the environmental risk assessment could not be performed. Consequently, the overall SSbD score for step 3 was assigned as level 2.

Step 4 – Environmental sustainability assessment

This section considered the two stages in the wastewater treatment proposed by Fuentes *et al.*: the fabrication of microreactors (manufacturing stage) and the subsequent production of MNPs (operation stage), conducted at both laboratory and industrial scales.[41] LCIA results were adapted to the SSbD score proposed by Caldeira *et al.*, which focuses on assess the degree of improvement relatively to the emerging technology compared with a reference.[1] As mentioned above, impact categories are categorized in four levels and the calculation of the level score is based on the percentage of improvement in eqn (1). Subsequently, a level is achieved when the process achieves a score of at least 2 in all impact categories within that level. The scoring considered in this step is reported in SI, Table S21.

$$\text{Improvement}\,(\%) = \frac{\text{I.C.}^{\text{a}}_{\text{ref}} - \text{I.C.}^{\text{a}}_{\text{alt}}}{\text{I.C.}^{\text{a}}_{\text{ref}}} \quad (1)$$

$\text{I.C.}^{\text{a}}_{\text{ref}}$ refers the impact category value of the reference process and $\text{I.C.}^{\text{a}}_{\text{alt}}$ is the value of the same impact category of the alternative process.

To carry out the calculation, reference processes were defined for both stages (manufacturing and operation). The reference process in the manufacturing stage represents a conventional approach to emerging technology for wastewater treatment, employing microfluidic devices equipped with rivet fittings. In contrast, the comparative process, as proposed by Fuentes *et al.*, introduces a novel alternative aimed at improving environmental performance.[41] This alternative involves substituting rivets with PEEK fittings, a change intended to enhance sustainability outcomes.

On the other hand, the reference process in the operation stage is related to the synthesis of MNPs with microfluidic devices. Based on the previous results in steps 1 and 2, the TMAH substitution is imperative as a mitigation strategy in the process. Therefore, the alternative approach considered a new reagent. Several substances have been reported in literature to prevent the agglomeration of magnetic nanoparticles.[44] Surfactants such as oleic acid, chitosan, polyethylene glycol (PEG), lauric acid, and sodium oleate have been proved to coated nanoparticles to avoid agglomeration.[45–49] Alternatively, sodium metasilicate has been investigated for surface modification of MNPs.[50] This reagent was used as an alternative to avoid agglomeration and assess the environmental performance of the process. Impact assessment results are shown in SI, Tables S22 to S25.

To quantitatively assess the efficacy of these proposed alternative approaches, SSbD scores were calculated as indicators of improvement percentages. The results for the manufacturing stage, as summarized in Table 3, reveal significant improvement percentages across various impact categories, surpassing a threshold of 40% in all cases. These improvements indicate that the use of PEEK fittings has a positive effect on the environmental performance of the manufacturing process. Consequently, the overall SSbD level obtained was 4.

For the operation stage, the results also indicate a high level of improvement in major impact categories. Based on these findings, the process passed three levels of environmental performance criteria. However, it failed to meet the pollution criteria. The failure in pollution criteria is primarily linked to the category of fine particulate matter formation. The use of sodium metasilicate, although effective in preventing nanoparticle agglomeration, contributed to a high impact in this specific category. This high impact highlights the need for further refinement or alternative solutions to mitigate the formation of fine particulate matter while maintaining the overall benefits.

These findings underscore the potential of the proposed alternative process to significantly consolidate environmental sustainability within the context of the emerging technology for wastewater treatment. By identifying the most impactful categories and life cycle stages, this study provides significant insights for optimizing process design. Specifically, the replacement of rivets with PEEK fittings in microreactors emerges as a promising strategy to elevate environmental performance and advance sustainable practices within the field.

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Table 3 SSbD scores for each impact category based on the degree of improvement relatively to the reference process at industrial scale

		Manufacturing stage Reference: Rivets fittings Alternative: PEEK fittings			Operation stage Reference: TMAH Alternative: Sodium metasilicate		
Criteria	Impact categories	Improvement (%)	SSbD score	Level	Improvement (%)	SSbD score	Level
Toxicity (criteria E1)	Human carcinogenic toxicity	92.35%	3	Pass the criteria	45.30%	3	Pass the criteria
	Human non-carcinogenic toxicity	99.26%	3		17.50%	2	
	Freshwater ecotoxicity	98.81%	3		17.20%	2	
	Marine ecotoxicity	98.91%	3		17.42%	2	
	Terrestrial ecotoxicity	99.24%	3		7.40%	2	
Climate change (criteria E2)	Global warming	45.97%	3	Pass the criteria	66.45%	3	Pass the criteria
Pollution (criteria E3)	Stratospheric ozone depletion	67.16%	3	Pass the criteria	85.89%	3	Fail the criteria
	Fine particulate matter formation	85.33%	3		−12.24%	0	
	Ionizing radiation	94.28%	3		19.01%	2	
	Ozone formation, human health	63.11%	3		69.89%	3	
	Ozone formation, terrestrial ecosystems	62.48%	3		70.17%	3	
	Terrestrial acidification	85.14%	3		68.83%	3	
	Freshwater eutrophication	97.61%	3		21.11%	3	
	Marine eutrophication	78.64%	3		92.90%	3	
Resources (criteria E4)	Water consumption	45.14%	3	Pass the criteria	25.21%	3	Pass the criteria
	Land use	51.74%	3		39.04%	3	
	Mineral resource scarcity	99.24%	3		14.05%	2	
	Fossil resource scarcity	42.91%	3		76.64%	3	
	SSbD level		4			3	

Step 5 – Exploratory social and economic assessments

In this study, inputs for MNPs production were identified within the defined system boundaries and linked through monetary values (USD) to reflect their contributions to the evaluated product system. Data related to materials, electricity, water, and transport were then used to assess the social performance of the proposed emerging technology and identify potential risk hotspots. However, it is important to emphasize that these results rely on country-level social data rather than information from any specific company, which inherently limits the precision of site-specific conclusions. Additionally, the applied Social Impact Weighting Method has notable limitations, as weighting social indicators involves subjective value judgments, lacks standardization, and can oversimplify complex social realities.

Fig. S4 in SI, shows the indicators associated with the social risks for workers. The highest risk identified for "Trade unionism", followed by "Human health – Safety measures", and "Fair salary". These findings are consistent with the broader social context in Colombia, where freedom of association faces systemic challenges despite a legal framework that guarantees labour rights. Trade unionists and community leaders are frequently exposed to harassment, violence, and even assassination, while weak institutional safeguards, low union density, and widespread use of temporary contracts further discourage collective bargaining. As a result, abstention from union membership may not reflect worker satisfaction but rather insecurity, mistrust, or perceived risks associated with organizing.[51]

On the other hand, other worker-related risks were also identified. Occupational health and safety standards are often insufficient, particularly in sectors such as chemicals, extractives, and manufacturing, where long or irregular working hours and unsafe environments remain common. Furthermore, risks related to the "Fair salary" category are significant in Colombia, as wages often fall below living wage levels, particularly in rural areas and in sectors with high informality. This contributes to persistent inequality and increases workers' vulnerability, especially where collective bargaining is weakened. These challenges are systemic and affect not only individual companies but also workers, local communities, and society at large.[52] It is important to note that the risks identified by PSILCA represent potential hotspots rather than confirmed impacts; additional field-based research is required to validate these findings. Nevertheless, the results underscore the importance of prioritizing freedom of association, fair working conditions, and workplace safety in the Colombian context.

Beyond the social dimension, economic sustainability was also evaluated. In a previous study, a discounted cash flow analysis for large-scale MNPs production using microreactors demonstrated strong economic performance.[53] The comprehensive evaluation of four large-scale production pathways showed that the microfluidics-based route offered the strongest economic appeal, achieving a Net Present Value of US$ 28 033 346, a modified internal rate of return of 19.73%, and a benefit–cost ratio of 2.07. This pathway also presented a high probability of profitability (50.06%), outperforming the other

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

scenarios. The use of microfluidic devices thus catalyses better financial returns and supports long-term economic sustainability for MNPs production.

By integrating these social and economic findings into the SSbD framework, the assessment provides a balanced understanding of both risks and opportunities. While the emerging technology with microreactors demonstrates strong economic feasibility, the identified social risk hotspots highlight the importance of ensuring that financial gains are not achieved at the expense of workers' rights, fair wages, or safe working conditions. It should be noted that a quantitative SSbD scoring was not performed in this study; such an evaluation will be addressed in future work to enable a more systematic comparison of safety and sustainability within the SSbD framework.

Overall SSbD evaluation

The application of the SSbD framework to the emerging technology for wastewater treatment enabled a structured evaluation of safety and sustainability across the first four steps. The proposed two-way aggregation approach was applied to determine the overall SSbD score.[1] Table 4 shows the results for raw materials classified with scores of 1 and 2, reflecting relatively good performance but also highlighting specific areas of concern.

For safety, PMMA, ethanol, and PEEK achieved a score of 1, while rivets, NaOH, iron(II), and iron(III) also obtained a score of 2. The lowest performance was observed for TMAH, which scored 0. This outcome was expected given the documented risks of TMAH, particularly its classification as a harmful substance with specific target organ toxicity upon repeated exposure (STOT-RE).

For environmental sustainability in the step 4, substitution options were explored to improve performance, particularly for rivets and TMAH. The resulting ratings of 3 and 2 across most materials suggest that meaningful improvements are possible through targeted changes in raw material selection. Although the environmental profile of the emerging technology is promising, additional optimizations will be needed to minimize long-term environmental burdens.

Overall, the results indicate that the innovation should be further pursued, as the combined safety and environmental scores demonstrate feasibility within the SSbD framework. However, there is clear potential to strengthen both safety and sustainability performance, particularly by addressing hazardous inputs and enhancing material substitution strategies.

A major limitation of the present work is that no quantitative SSbD scoring was performed for the social and economic dimensions. Step 5 provided only an exploratory assessment, and full integration of social risks and economic feasibility into the aggregation scheme will be the focus of future work. This gap underscores one of the broader challenges of SSbD: assessments are time- and data-intensive, requiring interdisciplinary expertise across toxicology, risk assessment, life cycle assessment, social sciences, and economics.

However, rather than delaying socio-economic assessment, this limitation highlights the need to adopt flexible and iterative evaluation strategies that evolve alongside the technology. Qualitative approaches, including expert opinion, stakeholder perspectives, and scenario-based analysis, can provide insights into potential risks, opportunities, and trade-offs that are not captured by quantitative metrics alone.[54] For example, expert judgement can help identify critical safety or operational concerns, while stakeholder engagement can reveal issues related to social acceptance, regulatory compliance, and usability in specific contexts. Scenario-based approaches can further support the exploration of future development pathways, including best-case and worst-case conditions for environmental and socio-economic performance.

In this study, integrating qualitative assessments would improve understanding of how the emerging technology for wastewater treatment may perform in real-world conditions. Factors such as accessibility, infrastructure, operational complexity, and cost could be explored through stakeholder input and expert judgement, complementing quantitative results and supporting more context-sensitive innovation pathways.

Table 4 Overall SSbD scores of raw materials, combining safety (steps 1–3) and environmental sustainability (step 4)

	Safety				Environmental sustainability					Social and economic sustainability	
					Step 4						
	Step 1 Level	Step 2 Level	Step 3 Level	Safety rating Steps 1–3	Toxicity Level	Climate change Level	Pollution Level	Resources Level	Environmental rating Step 4	Step 5 Level	Overall SSbD rating Level
PMMA	1	1	2	1	3	3	3	3	3	No SSbD scoring	1
Rivets	3	3	2	2	3	3	3	3	3		2
Ethanol	2	1	2	1	3	3	3	3	3		1
PEEK	1	1	2	1	3	3	3	3	3		1
NaOH	2	3	2	2	2	3	2	3	2		2
Iron(II)	2	3	2	2	2	3	2	3	2		2
Iron(III)	2	3	2	2	2	3	2	3	2		2
TMAH	0	0	2	0	2	3	2	3	2		0

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Future research should therefore integrate these qualitative approaches alongside quantitative methods to enable a more comprehensive SSbD evaluation of the proposed system.

Despite these challenges, the current application demonstrates the value of the SSbD framework in identifying opportunities and critical issues early in technology development. By gathering systematic information on chemical safety, environmental performance, and potential social and economic risks, the framework provides a foundation for designing technologies that are not only safe and environmentally sound but also socially responsible and economically viable. Looking ahead, the integration of all four sustainability pillars into a unified SSbD scoring system will be essential to ensure that innovation pathways are safer, comparable, and aligned with long-term sustainability goals considering social justice, competitiveness, and reduced carbon and environmental footprint.

The application of the SSbD framework to this case study provides also insights into its operationalization beyond its original focus on chemicals and materials. This study demonstrates that SSbD can be effectively extended to complex system-level technologies. However, this extension requires methodological flexibility, particularly in defining system boundaries and selecting appropriate indicators. These findings suggest that SSbD is not limited to chemical design but can serve as a broader framework for guiding sustainable innovation across domains such as environmental engineering, energy systems, and biotechnology.

A key lesson from this work is the importance of multiscale integration. Applying SSbD in this context required to link hazard assessment at the material level with environmental and operational considerations at the system level. This implies that successful implementation will depend on the ability to connect different layers of analysis in a coherent and transparent manner. In addition, the study highlights the need for iterative application, where SSbD is used not only as an assessment tool but as a design-support framework that evolves alongside technological development. For researchers and practitioners, several practical lessons emerge such as combining quantitative and qualitative approaches, addressing data gaps through expert judgement and stakeholder engagement, and fostering interdisciplinary collaboration. From a policy perspective, further development of SSbD by institutions such as the Joint Research Centre (JRC) and the European Commission should focus on providing more flexible and modular guidance by improving access to harmonized data and tools to support broader applicability across domains.

At the same time, the applicability of SSbD to non-EU regulatory and socio-economic contexts presents additional challenges. Differences in data availability, policy frameworks, infrastructure, and societal priorities may affect both the implementation and outcomes of SSbD assessment. Addressing these limitations requires a context-sensitive approach, incorporating locally relevant indicators, and participatory processes to capture societal needs and constraints.

Overall, this study suggests that the future development of SSbD should move toward a more flexible, integrative, and globally applicable framework. These advancements will ensure that the framework not only meets its objectives within the European context but also contributes meaningfully to global sustainability transitions.

Finally, the application of SSbD in the context of green chemistry opens important perspectives regarding environmental justice, which remain underexplored in current implementations.[55,56] Beyond improving safety and environmental performance, SSbD could contribute to identify and mitigate unequal exposure to chemical risks for workers and vulnerable communities who are often disproportionately affected. It also provides an opportunity to examine how responsibilities and risks are distributed along the value chain, including potential burden shifting between life cycle stages or across regions. Although this approach was beyond the scope of this study, future research should explore how SSbD can incorporate equity-oriented indicators and stakeholder or community engagement to better capture context-specific impacts and support more socially responsible innovation pathways.

Conclusions

This study applied the SSbD framework to an emerging technology for wastewater treatment, integrating safety, environmental, social, and economic considerations. Findings revealed that most raw materials achieved moderate SSbD scores, with TMAH identified as the main safety hotspot. Substitution strategies, such as replacing rivets fitting with PEEK and substituting TMAH with sodium metasilicate, demonstrated potential to improve environmental performance. While the economic evaluation highlighted strong feasibility of the emerging technology, social risks remain critical challenges in the Colombian context. Notably, this work represents the first application of the SSbD framework that includes social assessment results, highlighting the relevance and feasibility of integrating social dimensions at early innovation stages.

Moreover, this study highlights a broader challenge within the SSbD framework. A lack of socio-economic tools for early innovation phases limits the systematic inclusion of social criteria. Addressing this gap requires the development of robust indicators that can capture risks such as low wages, informal work, and weak labor protections, and their integration into SSbD workflows. Overall, the results demonstrate that the technology holds promise for safe and sustainable deployment, but further efforts are needed to mitigate social risks and enhance worker protection.

Importantly, this work demonstrates how the SSbD framework can be leveraged as a green advance to align technological innovation with sustainability transitions. By adopting a life cycle approach, SSbD provides an opportunity to identify hotspots, guide material substitution, and align technological innovation with societal needs.

 This journal is © The Royal Society of Chemistry 2026

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM. This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

In this sense, the technology assessed here represents a meaningful advance in safety and sustainability, offering pathways to cleaner water treatment processes while addressing pressing global challenges. Future work will extend the initial social-economic assessment to include quantitative scoring, enabling a more comprehensive evaluation across the full life cycle. In addition, future SSbD applications should also incorporate supply-risk considerations, including the role of critical raw materials (CRM) and geopolitical risks, to ensure long-term material availability, resilience, and stability of emerging technologies. Ultimately, the integration of safety, environmental, social, and economic aspects through the SSbD framework reinforces its role as a catalyst for fostering the development of innovative, competitive technologies that contribute to a safer, greener, and more equitable future.

Author contributions

O. P. F.: conceptualization, data curation, investigation, methodology, software, validation, visualization, writing – original draft, writing – review & editing. A. G. P.: conceptualization, methodology, investigation, writing – review & editing. J. F. O.: conceptualization, supervision, writing – review & editing. G. S.: conceptualization, funding acquisition, methodology, supervision, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

The supporting data has been provided as part of the supplementary information (SI). Supplementary information is available. The supplementary information compiles data on the reactor design, wastewater characteristics, material hazards, exposure and risk assessments, nanoparticle toxicity, environmental life cycle impacts, and social indicators, providing a comprehensive evaluation of the process's safety and sustainability. See DOI: https://doi.org/10.1039/d5gc06437f.

Acknowledgements

The authors gratefully acknowledge funding from the France 2030 program, managed by the French National Research Agency (ANR), under grant agreement no. ANR-22-PETA-0010. The first author is supported by this grant.

The authors would like to sincerely thank Dr Veronica Akle for her valuable contribution to this work, particularly for conducting and supporting the zebrafish (*Danio rerio*) experiments, which were essential for the assessment of the biological and toxicological aspects of the study.

Notes and references

1 C. Caldeira, R. Farcal, I. Garmendia Aguirre, L. Mancini, D. Tosches, A. Amelio, K. Rasmussen, H. Rauscher, J. Riego Sintes and S. Sala, *Safe and sustainable by design chemicals and materials – Framework for the definition of criteria and evaluation procedure for chemicals and materials*, Publications Office of the European Union, 2022.
2 J. van Dijk, A. Sharma, B. Nowack, Z. Wang and M. Scheringer, *Environ. Sci. Technol.*, 2025, **59**, 14832–14841.
3 C. Apel, K. Kümmerer, A. Sudheshwar, B. Nowack, C. Som, C. Colin, L. Walter, J. Breukelaar, M. Meeus, B. Ildefonso, D. Petrovykh, C. Elyahmadi, E. Huttunen-Saarivirta, A. Dierckx, A. C. Devic, E. Valsami-Jones, M. Brennan, C. Rocca, J. Scheper, E. Strömberg and L. G. Soeteman-Hernández, *Curr. Opin. Green Sustainable Chem.*, 2024, **45**, 100876.
4 E. Abbate and G. Aguirre, *Safe and Sustainable by Design chemicals and materials - Methodological Guidance*, 2024.
5 L. Pizzol, A. Livieri, B. Salieri, L. Farcal, L. G. Soeteman-Hernández, H. Rauscher, A. Zabeo, M. Blosi, A. L. Costa, W. Peijnenburg, S. Stoycheva, N. Hunt, M. J. López-Tendero, C. Salgado, J. J. Reinosa, J. F. Fernández and D. Hristozov, *Cleaner Environ. Syst.*, 2023, **10**, 100132.
6 L. A. Morales-Marín, E. A. Rodríguez and F. Jaramillo, *Hydrol. Sci. J.*, 2026, 1–20.
7 Y. Aranguren-Díaz, N. J. Galán-Freyle, A. Guerra, A. Manares-Romero, L. C. Pacheco-Londoño, A. Romero-Coronado, N. Vidal-Figueroa and E. Machado-Sierra, *Water*, 2024, **16**(5), DOI: 10.3390/w16050685.
8 L. Casso-Hartmann, P. Rojas-Lamos, K. McCourt, I. Vélez-Torres, L. E. Barba-Ho, B. W. Bolaños, C. L. Montes, J. Mosquera and D. Vanegas, *Sci. Total Environ.*, 2022, **852**, 158417.
9 P. S. Khoo, R. A. Ilyas, A. Aiman, J. S. Wei, A. Yousef, N. Anis, M. Y. M. Zuhri, H. Abral, N. H. Sari, E. Syafri and M. Mahardika, *Int. J. Biol. Macromol.*, 2024, **278**, 135088.
10 R. Sharma, P. C. Nath, Y. K. Mohanta, B. Bhunia, B. Mishra, M. Sharma, S. Suri, M. Bhaswant, P. K. Nayak and K. Sridhar, *Int. J. Biol. Macromol.*, 2024, **256**, 128517.
11 G. A. Kallawar and B. A. Bhanvase, *Environ. Sci. Pollut. Res.*, 2024, **31**, 1748–1789.
12 J. Tripathy, A. Mishra, M. Pandey, R. R. Thakur, S. Chand, P. R. Rout and M. K. Shahid, *Water*, 2024, **16**(11), DOI: 10.3390/w16111481.
13 B. Kamenická, *Sci. Total Environ.*, 2025, **969**, 178897.
14 G. Dong, B. Chen, B. Liu, L. J. Hounjet, Y. Cao, S. R. Stoyanov, M. Yang and B. Zhang, *Water Res.*, 2022, **211**, 118047.
15 Y. Qi, J. Zeng and K. Wang, *Can. J. Chem. Eng.*, 2025, **103**, 2826–2836.
16 L. D. Sotelo, D. C. Sotelo, N. Ornelas-Soto, J. C. Cruz and J. F. Osma, *Membranes*, 2022, **12**(3), DOI: 10.3390/membranes12030298.

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

17 H. Oladipo, J. Adewole, L. Abidoye, S. Al Hinai, S. Al Kharusi and M. Al Salti, *Chem. Pap.*, 2024, **78**, 6395–6403.
18 E. Parandi, M. Mousavi, H. Kiani, H. Rashidi Nodeh, J. Cho and S. Rezania, *Energy Convers. Manage.*, 2023, **295**, 117616.
19 S. Xia, B. Liu, Z. Chen and J. Xu, *Chem. Eng. Sci.*, 2025, **304**, 120985.
20 Y. Chen, J. Yu, Y. Yang, F. Huo and C. Li, *Chem. Eng. J.*, 2023, **455**, 140670.
21 K. Vijaya Bhaskar, M. Rashed, K. Subrahmanya Bhat, J. Lee, K.-H. Kim and K. Buruga, *Process Saf. Environ. Prot.*, 2024, **192**, 437–449.
22 P. A. Peñaranda, M. J. Noguera, S. L. Florez, J. Husserl, N. Ornelas-Soto, J. C. Cruz and J. F. Osma, *Nanomaterials*, 2022, **12**, 10.
23 R. S. Abiev, A. M. Nikolaev, A. S. Kovalenko, Y. E. Gorshkova, N. V. Tsvigun, A. E. Baranchikov, G. P. Kopitsa and O. A. Shilova, *Chem. Eng. Res. Des.*, 2024, **205**, 335–342.
24 E. Parandi, M. Mousavi, H. Kiani, S. Nasirijoonaghani, M. Rouhi, H. Rashidi Nodeh, E. Assadpour, F. Zhang and S. M. Jafari, *Chem. Eng. J.*, 2024, **496**, 153900.
25 S. L. Florez, A. L. Campaña, M. J. Noguera, V. Quezada, O. P. Fuentes, J. C. Cruz and J. F. Osma, *Micromachines*, 2022, **13**(6), 6.
26 C.-Y. Yang, C.-Y. Wang, N. Ni Myint, Y.-C. Chen, P. Srinophakun and Y.-Y. Chiang, *Green Chem.*, 2025, **27**, 13214–13234.
27 V. Hessel, S. Mukherjee, S. Mitra, A. Goswami, N. N. Tran, F. Ferlin, L. Vaccaro, F. M. Galogahi, N.-T. Nguyen and M. Escribà-Gelonch, *Green Chem.*, 2024, **26**, 9503–9528.
28 F. Pitaro, S. Seeger and B. Nowack, *Environ. Int.*, 2025, **197**, 109345.
29 C. Caldeira, I. Garmendia Aguirre, R. Tosches, D. Farcal, L. Mancini, D. Lipsa, K. Rasmussen, H. Rauscher, J. Riego Sintes and S. Sala, *Safe and Sustainable by Design chemicals and materials - Application of the SSbD framework to case studies*, 2023.
30 A. Mech, S. Gottardo, V. Amenta, A. Amodio, S. Belz, S. Bøwadt, J. Drbohlavová, L. Farcal, P. Jantunen, A. Małyska, K. Rasmussen, J. Riego Sintes and H. Rauscher, *Regul. Toxicol. Pharmacol.*, 2022, **128**, 105093.
31 S. Valdivia and G. Sonnemann, *Handbook on Life Cycle Sustainability Assessment*, Edward Elgar Publishing, Cheltenham, UK, 2024.
32 ECHA, Chesar tool, https://chesar.echa.europa.eu/.
33 ECHA, Use maps, https://echa.europa.eu/csr-es-roadmap/use-maps/concept.
34 A. Guillén-Pacheco, Y. Ardila, P. A. Peñaranda, M. Bejarano, R. Rivas, J. F. Osma and V. Akle, *Chemosphere*, 2024, **358**, 142081.
35 E. Haque and A. C. Ward, *Nanomaterials*, 2018, **8**(7), DOI: 10.3390/nano8070561.
36 R. N. W. Kettleborough, E. M. Busch-Nentwich, S. A. Harvey, C. M. Dooley, E. de Bruijn, F. van Eeden, I. Sealy, R. J. White, C. Herd, I. J. Nijman, F. Fényes, S. Mehroke, C. Scahill, R. Gibbons, N. Wali, S. Carruthers, A. Hall, J. Yen, E. Cuppen and D. L. Stemple, *Nature*, 2013, **496**, 494–497.
37 K. Howe, M. D. Clark, C. F. Torroja, J. Torrance, C. Berthelot, M. Muffato, J. E. Collins, S. Humphray, K. McLaren, L. Matthews, S. McLaren, I. Sealy, M. Caccamo, C. Churcher, C. Scott, J. C. Barrett, R. Koch, G.-J. Rauch, S. White, W. Chow, B. Kilian, L. T. Quintais, J. A. Guerra-Assunção, Y. Zhou, Y. Gu, J. Yen, J.-H. Vogel, T. Eyre, S. Redmond, R. Banerjee, J. Chi, B. Fu, E. Langley, S. F. Maguire, G. K. Laird, D. Lloyd, E. Kenyon, S. Donaldson, H. Sehra, J. Almeida-King, J. Loveland, S. Trevanion, M. Jones, M. Quail, D. Willey, A. Hunt, J. Burton, S. Sims, K. McLay, B. Plumb, J. Davis, C. Clee, K. Oliver, R. Clark, C. Riddle, D. Elliott, G. Threadgold, G. Harden, D. Ware, S. Begum, B. Mortimore, G. Kerry, P. Heath, B. Phillimore, A. Tracey, N. Corby, M. Dunn, C. Johnson, J. Wood, S. Clark, S. Pelan, G. Griffiths, M. Smith, R. Glithero, P. Howden, N. Barker, C. Lloyd, C. Stevens, J. Harley, K. Holt, G. Panagiotidis, J. Lovell, H. Beasley, C. Henderson, D. Gordon, K. Auger, D. Wright, J. Collins, C. Raisen, L. Dyer, K. Leung, L. Robertson, K. Ambridge, D. Leongamornlert, S. McGuire, R. Gilderthorp, C. Griffiths, D. Manthravadi, S. Nichol, G. Barker, S. Whitehead, M. Kay, J. Brown, C. Murnane, E. Gray, M. Humphries, N. Sycamore, D. Barker, D. Saunders, J. Wallis, A. Babbage, S. Hammond, M. Mashreghi-Mohammadi, L. Barr, S. Martin, P. Wray, A. Ellington, N. Matthews, M. Ellwood, R. Woodmansey, G. Clark, J. D. Cooper, A. Tromans, D. Grafham, C. Skuce, R. Pandian, R. Andrews, E. Harrison, A. Kimberley, J. Garnett, N. Fosker, R. Hall, P. Garner, D. Kelly, C. Bird, S. Palmer, I. Gehring, A. Berger, C. M. Dooley, Z. Ersan-Ürün, C. Eser, H. Geiger, M. Geisler, L. Karotki, A. Kirn, J. Konantz, M. Konantz, M. Oberländer, S. Rudolph-Geiger, M. Teucke, C. Lanz, G. Raddatz, K. Osoegawa, B. Zhu, A. Rapp, S. Widaa, C. Langford, F. Yang, S. C. Schuster, N. P. Carter, J. Harrow, Z. Ning, J. Herrero, S. M. J. Searle, A. Enright, R. Geisler, R. H. A. Plasterk, C. Lee, M. Westerfield, P. J. de Jong, L. I. Zon, J. H. Postlethwait, C. Nüsslein-Volhard, T. J. P. Hubbard, H. R. Crollius, J. Rogers and D. L. Stemple, *Nature*, 2013, **496**, 498–503.
38 A. Guillén, Y. Ardila, M. J. Noguera, A. L. Campaña, M. Bejarano, V. Akle and J. F. Osma, *Nanomaterials*, 2022, **12**(3), DOI: 10.3390/nano12030489.
39 F. Busquet, R. Strecker, J. M. Rawlings, S. E. Belanger, T. Braunbeck, G. J. Carr, P. Cenijn, P. Fochtman, A. Gourmelon, N. Hübler, A. Kleensang, M. Knöbel, C. Kussatz, J. Legler, A. Lillicrap, F. Martínez-Jerónimo, C. Polleichtner, H. Rzodeczko, E. Salinas, K. E. Schneider, S. Scholz, E.-J. van den Brandhof, L. T. M. van der Ven, S. Walter-Rohde, S. Weigt, H. Witters and M. Halder, *Regul. Toxicol. Pharmacol.*, 2014, **69**, 496–511.
40 A. Henríquez Martínez, L. C. Ávila, M. A. Pulido, Y. A. Ardila, V. Akle and N. I. Bloch, *Front. Physiol.*, 2022, **13**, DOI: 10.3389/fphys.2022.856778.

Open Access Article. Published on 29 April 2026. Downloaded on 5/21/2026 5:32:34 PM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

41 O. P. Fuentes, J. C. Cruz, E. Mignard, G. Sonnemann and J. F. Osma, *ACS Sustainable Chem. Eng.*, 2023, **11**, 6932–6943.

42 ISO, ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework, https://www.iso.org/standard/37456.html, (accessed 21 March 2025).

43 E. S. Andrews, L.-P. Barthel, T. Beck, C. Benoît, A. Ciroth, C. Cucuzzella, C.-O. Gensch, J. Hébert, P. Lesage, A. Manhart, P. Mazeau, B. Mazijn, A.-L. Methot, A. Moberg, G. Norris, J. Parent, S. Prakash, J.-P. Reveret, S. Spillemaeckers, C. M. L. Ugaya, S. Valdivia and B. Weidema, *Guidelines for Social Life Cycle Assessment of Products*, 2009.

44 T. Guo, X. Bian and C. Yang, *Phys. A*, 2015, **438**, 560–567.

45 D. K. Kim, Y. Zhang, W. Voit, K. V. Rao and M. Muhammed, *J. Magn. Magn. Mater.*, 2001, **225**, 30–36.

46 L. Zhang, R. He and H.-C. Gu, *Appl. Surf. Sci.*, 2006, **253**, 2611–2617.

47 Y. Köseoğlu, *J. Magn. Magn. Mater.*, 2006, **300**, e327–e330.

48 U. Klekotka, E. Zambrzycka-Szelewa, D. Satuła and B. Kalska-Szostko, *Materials*, 2021, **14**(17), DOI: 10.3390/ma14175069.

49 B. Kalska-Szostko, M. Zubowska and D. Satula, *Acta Phys. Pol., A*, 2006, **109**, 365–369.

50 S. E. Favela-Camacho, E. J. Samaniego-Benítez, A. Godínez-García, L. M. Avilés-Arellano and J. F. Pérez-Robles, *Colloids Surf., A*, 2019, **574**, 29–35.

51 P. Lenzo, M. Traverso, R. Salomone and G. Ioppolo, *Sustainability*, 2017, **9**(11), DOI: 10.3390/su9112092.

52 M. Koese, C. F. Blanco, V. B. Vert and M. G. Vijver, *J. Ind. Ecol.*, 2023, **27**, 223–237.

53 O. P. Fuentes, D. M. Trujillo, M. E. Sánchez, A. L. Abrego-Perez, J. F. Osma and J. C. Cruz, *ACS Sustainable Chem. Eng.*, 2024, **12**, 760–772.

54 R. Graham, J.-M. Couture, S. Nadeau and R. Johnson, *Int. J. Life Cycle Assess.*, 2024, **29**, 2032–2059.

55 M. K. M. Lane, H. E. Rudel, J. A. Wilson, H. C. Erythropel, A. Backhaus, E. B. Gilcher, M. Ishii, C. F. Jean, F. Lin, T. D. Muellers, T. Wang, G. Torres, D. E. Taylor, P. T. Anastas and J. B. Zimmerman, *Nat. Sustain.*, 2023, **6**, 502–512.

56 C. Brinkley and J. Wagner, *J. Am. Plann. Assoc.*, 2024, **90**, 63–76.