Article

Implementing Social Life Cycle Assessment for Safe and Sustainable by Design Advanced Materials: A Case Study of Multicomponent Anti-Stick Coatings

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ABSTRACT

The Safe and Sustainable by Design (SSbD) framework for chemicals and materials was established under the European Green Deal *Chemical Strategy for Sustainability*, aiming for a zero-pollution economy and a toxic-free environment. In line with the European Commission's SSbD recommendation and framework, a pre-market sustainability assessment must take a life cycle perspective covering all pillars of sustainability: environmental, social, and economic. While environmental and economic assessments are well established, Social Life Cycle Assessment (S-LCA) has been less explored, especially when applied to advanced materials. To contribute to Step 5 of the SSbD Framework, this study presents a S-LCA applied during early stages of product development and optimisation. The case study concerns a novel PFAS-free anti-sticking coating, assessed in comparison with a conventional benchmark. The screening-level analysis identified potential social risk hotspots along the supply chain. Results indicate that differences between alternatives are predominantly driven by suppliers' geographical locations rather than by process-specific characteristics. The results highlight the value of early-stage social assessments in supporting informed decision-making during research and

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development, increasing awareness of potential supply-chain risks, and guiding innovation toward more sustainable outcomes.

KEYWORDS: SSbD; Social Life Cycle Assessment (S-LCA); SHDB; AdMa; nanomaterials

INTRODUCTION

The European Green Deal introduces new policies addressing climate, biodiversity, circularity, human health and environmental protection with the aim of transforming the EU into a more sustainable and competitive economy [1]. Within this ambitious plan, pollution from all sources should be reduced to progress towards a zero-pollution economy for a toxic-free environment. The Chemicals Strategy for Sustainability (CSS) and the Zero Pollution Action Plan identify actions to reach these objectives calling for the adoption of the Safe and Sustainable by Design (SSbD) paradigm when developing new chemicals and materials [2,3]. To support practical SSbD implementation by the industries, the European Commission (EC) published the Recommendation for establishing a European assessment framework for SSbD chemicals and materials [4], which is based on a holistic scientific-technical approach developed by the EC's Joint Research Centre [5]. In the paper, the EC Recommendation [4] in combination with its scientific-technical background [5], the Methodological Guidance [6] will be called the "SSbD Framework". Acknowledging that the SSbD Framework is under revision, the present study was conducted prior to the publication of final revised version; therefore, it follows the SSbD Framework version that was available at the time of the analysis [7].

The SSbD Framework is organised in 5 steps, which evaluates chemicals and materials safety (Step 1–3), environmental impacts (Step 4), and socio-economic sustainability (Step 5). Each step is performed in an iterative and tiered manner, aligning with increased data availability while the innovation is developed. In this paper, we focus on the operationalization of Step 5 of the JRC Framework discussing the role of simplified S-LCA as an effective tool for supporting the operationalisation of the SSbD Framework by industry. As definition of simplified, the SSbD Framework's is adopted.

Sustainability assessment is aligned with the triple bottom line core concept [8] covering the environmental, social, and economic dimensions. While environmental and economic assessment have a long history of application and strong methodological roots in the established Life Cycle Assessment (LCA) [9,10] and Life Cycle Costing (LCC) [11–13] methodologies [14], Social Life Cycle Assessment (S-LCA) methodological development is happening in recent years, aligning with the rising interest in including the social dimension into sustainability assessments. The dedicated ISO standard has been published in Autumn 2024 [15]. Sufficient practical implementations of the methodologies are still lacking, especially when applied to advanced materials (AdMa) [16]. To the authors knowledge, S-LCA has been applied in few works, with different aims: to guide alternative process selection [17], to support the selection of a supply chain [18], or to contribute to the sustainability profile of products in companies' portfolios [19]. Likewise, only very few studies are addressing S-LCA in the SSbD context: the JRC technical report on application of the SSbD framework to a set of case studies carried out a Social Inventory as part of an explorative socio/economic assessment for Step 5 [20]; the BIO-SUSHY project presented during the SETAC2025 conference an approach to carry out a qualitative social assessment, as a first step to assess social sustainability.

Nonetheless, social well-being and socially responsible production are fundamental criteria for evaluating the sustainability of a new product. AdMa are increasingly being used in many key industrial sectors such as construction, structural and functional materials, active ingredients, food, healthcare, energy, cosmetics, and electronics. Among AdMa, nanomaterials and nano-enabled product are gaining interest for the unprecedented technological benefits they can offer. Not all AdMa are nanomaterials [4], but in many cases, they are nanocomposites formed by two or more functional components (e.g., nanoparticles, nanocrystals, organic molecules) conjugated by strong molecular bonds, or by a nanomaterial with a unique chemical origin modified by hard or soft coatings [21,22]. These new multicomponent materials are very promising innovation, but they can also pose unforeseen safety and sustainability challenges [18]. Therefore, as any emerging chemical/material, the human health, and ecological risks as well as the environmental, social, and economic sustainability of AdMa should be thoroughly assessed. This should be done already in the early stages of product development when fundamental changes to the (choice of) materials and production processes can still be made at acceptable cost. However, there is a substantial need to develop and test screening level methods capable of assessing the materials/products from a life cycle perspective to identify 'hotspots of concern'. We define "hotspots of concern" as processes that might be potential sources of impacts, such as air emissions throughout the product's life cycle when considering environmental impacts or sourcing from countries reported for poor working conditions when considering social impacts. These include safety and/or sustainability concerns that need to be addressed before committing additional resources to further product development. The results are targeted at industries as a basis for SSbD decision making in the early R&D stages of innovation.

The goal of the H2020 SUNSHINE project (GA952924) has been to address this challenge. SUNSHINE proposed an overarching SSbD approach [23], which has been further advanced in the HEU SUNRISE project (GA101137324) and practically tested in a suite of industrial case studies involving AdMa. This approach applies life cycle thinking to identify opportunities for improvements in terms of safety and sustainability along the entire supply chains of AdMa and the products enabled by them. The methodology is implemented in tiers of assessment with each tier addressing a different stage of the innovation process and increasing the complexity of the employed assessment methods as well as the time, resources, data, and level of expertise required for their application. In the SSbD context, early application of life cycle assessments of environmental, economic, and social impacts plays a key role in identifying, mitigating, and ultimately resolving potential issues in the product development and optimisation stages, thus providing the opportunity to integrate feedback more efficiently and leaving room for improvement before the market release. Despite the increasing relevance of AdMa in sustainable industrial applications, S-LCA studies addressing innovative materials remain limited, particularly within the SSbD framework. To address this need, in the manuscript we focus on the operationalization of Step 5 of the JRC Framework, discussing the role of simplified S-LCA as an effective tool for supporting its operationalisation by industry. This study is part of a broader assessment that includes a qualitative sustainability assessment applied in the early stage of material development, and an LCA and LCC of the same product, with the aim of supporting a comprehensive sustainability SSbD evaluation [24]. This will be achieved through the application of comparative S-LCA to a real product: a novel PFAS-free anti-sticking coating used in the bakery industry (i.e., coating of baking trays and pans) compared to a conventional anti-stick coating (Teflon), followed by a social risk hotspots assessment of the product.

The manuscript is organised as follows. Section (METHODS) presents the methods used to perform the simplified S-LCA. Section (Results) reports the obtained results and interprets them. Section (Discussion) discusses the results, while Section (Conclusions and Recommendations) draws conclusions and suggests the direction of further studies.

METHODS

S-LCA

The perspective S-LCA presented in this manuscript is part of the tiered SSbD approach which was developed in the H2020 SUNSHINE and HEU SUNRISE projects in alignment with the recent EC's SSbD recommendation (C (2022) 8854) [4] and framework [5]. The SUNSHINE/SUNRISE approach is composed of three tiers, applied at each stage of the innovation process and along the lifecycle of AdMa [25]. Tier 1 is composed of a qualitative self-assessment questionnaire to identify 'hotspots of concerns' already in the early R&D steps and at low Technology Readiness Levels (TRLs) [23]. Tier 2 is a semi-quantitative assessment based on a weight of evidence approach applied in the product optimisation phase when a mix of qualitative and quantitative data are already available [16]. Finally, Tier 3 involves quantitative safety (regulatory risk assessment) and sustainability impact assessment (LCA, LCC, and S-LCA) for materials/products (ready to be) released on the market. The presented S-LCA study falls within Tier 3 of the above tiered SSbD approach, covering the social assessment of Step 5 of the JRC Framework. However, its simplified nature makes is suitable to apply also in the early R&D and product optimisation stages if enough data for the target materials/products are available.

Life Cycle Assessment methodologies generally support decision making processes in a retrospective, or ex-post, perspective, meaning that they are applied to organizations and products already at the market level. In SSbD, innovations are still being improved and tested, and the role of sustainability assessors is to provide guidance during these early phases. To fit the SSbD concept, LCA is applied in while product development is ongoing, and when material and process design changes are easier and less costly to implement. The task bears the challenge of measuring the potential impacts at the lab or bench scale, when the available data are often limited, producing preliminary results that allow to subsequently evaluate environmental, social, and economic impacts of the developed products from a life cycle perspective. This study builds up on these premises, proposing a S-LCA of a nano-enabled advanced material that comparatively assesses potential social risks of the supply chains. The study was conducted according to the "Guidelines for Social Life Cycle Assessment of Products and Organizations" [26] considering the following relevant stakeholder groups: workers, local communities, value chain actors and society. Consumers are not included because the study does not cover the use phase of the product, while children are not included in the database version used for this case study. The impacts for each targeted stakeholder group were assessed using the Social Hotspot Database (SHDB) as described in section (Social Hotspot Database (SHDB)).

The study structure coincides with the four phases outlined in the ISO standard 14075 [15]. Therefore, the S-LCA study is organized into: Goal and Scope definition, Life Cycle Inventory, Life Cycle Impact Assessment, and Interpretation. For each phase, a short description is provided in the next sections.

Goal and Scope definition

In this phase, as in Environmental LCA, it is required to state the reason to carry out the study, the envisioned use of results, the target to which they are destined, the functional unit, the selected system, and the assumptions made. The process is iterative; if new information is available during the following phases that can provide new insights it is possible to adjust the goal and scope previously defined.

Life Cycle Inventory

This assessment was conducted following the S-LCA guidelines and with the SHDB available for SimaPro. The SHDB includes twenty-five impact subcategories and five aggregated impact categories that were all considered in the assessment. Figure 1 reports all the stakeholder subcategories, categories, and the stakeholders to which they refer. The subcategories are assessed through 160 social impact indicators, varying in number and type for each subcategory. An example is the Average wage indicator, that for the "wage" subcategory was compared to the country-level Sweatfree wages, national minimum wages set by governments, and country level living wages [27]. Indicators are fed by different sources of data, as described in section (Life Cycle Impact Assessment). As it will be detailed below, the SHDB integrates the calculation method Social Hotspot index, where the social risk is expressed for each impact subcategory and category in medium risk hours equivalent (mrheq). These are calculated by multiplying the database data on working hours necessary to produce a certain value of good by the medium risk level, spanning from very high to low.

Figure 1. Stakeholders, categories, and subcategories considered in the SHDB.

Life Cycle Impact Assessment

The impact assessment in S-LCA can be performed according to two different approaches: Reference Scale Assessment (RS S-LCA) and Impact Pathway Assessment (IP S-LCA). RS S-LCA aims at assessing the impact of a system based on its social performances or risks, while IP S-LCA assesses social consequences linking them in cause-effect relations.

The SHDB provides the Social Hotspot index reference scale impact assessment method, a RS S-LCA method available for the software SimaPro. The method was developed by the provider of the SHDB (i.e., the NewEarth B company) and includes a reference scale for the estimation of the probability of social risks to occur. The risk levels are organized into classes, that provide the reference scale used to assess the potential social impact, weighted as reported in Norris et al. [27]. Risk levels vary from a very high, high, and medium class to a low risk level class. Each class is associated with a characterization factor that describes the severity of presence of a social issue, or its probability to occur (very high = 10, high = 5, medium = 1, low = 0.1). The characterization factor is used to convert the data collected for each impact indicator in medium risk hour equivalents (mrheq), that quantify the potential social impact of the product system on that subcategory. Worker hours are used as a proxy for work intensity, to point out processes in the supply chain where more human activity is happening. This relates to the probability of encountering social risks and therefore can guide the prioritization of improvements. The use of working hours has limitations especially in representing potential impacts on local communities and societies. However, it is considered as the best available indicator to model social impact distribution along the whole supply chain [27]. The impact result depends on the specific data collected for each subcategory indicator and the risk level, which is determined based on data distribution, expert judgment, and literature. Information on social risks is collected from various sources and references publicly available (e.g., Global Reporting Index, Sustainable Development Goals, NGO reports, International Labor Organization, World Health Organization, World Bank, ISO 26000). These data feed different indicators for the assessment of the impact subcategories. Each subcategory can be built on a composite or single indicator depending on resource availability. Since the information is gathered from publicly available documentation, there may be a scarcity of relevant data, which can result in less robust indicators. The construction of indicators is thoroughly reported in Norris et al. [27].

Interpretation

In this final phase, results are analysed in depth, summarized, and discussed to produce a final assessment providing conclusions, recommendations, and information for decision-making steps. To improve the results, the preferred option would be to collect primary data on site by asking directly affected stakeholders. This is recommended both in the Guidelines for S-LCA [26] and in the Supporting documentation to SHDB [27]. Surveys would be the ideal tool to update the study with testimonies on both negative and positive social impacts, once the SHDB has supported the hotspots identification. An alternative or complementary prior step would be to carry out a desk review. This may be an advantage for production companies who are not willing to allocate further time and resources on the S-LCA analysis, while wanting to obtain a more specific picture of their product's potential social impacts by assessing the social behaviours of the value chain. This might include a more general literature research or a deep investigation into the supply chain social reports and local NGOs repositories. Based on the results obtained, the practitioners can decide which option(s) works better for the interpretation and validation of the results their S-LCA studies.

Social Hotspot Database (SHDB)

The assessment reported in this paper has been developed by using the SHDB. Data in the SHDB cover the supply chain composition, the labour intensity, and the information on social risk. Supply chains are geographically specific and generated using the Global Trade Analysis Project (GTAP) model. Data are organized by country, where for each country, a list of relevant sectors is provided by using the GTAP model. The country/sector data is expressed in worker hours, which is an activity variable (The activity variable is a measure of process activity which can be related to process output. Activity variables, scaled by the output of each relevant process, are used to reflect the share of a given activity associated with each unit process. As such, it does not represent an impact but rather an elementary flow used to compare the intensity of the processes and aggregate impact assessment results [26].) which identifies where the human activity is located in the supply chain, and how intensely. The activity variable, even if explicitly linked only to the workers stakeholder category, is considered the best mean to assess the scale of social issues that might take place for all stakeholder categories along the supply chain [27].

The Case Study of a novel PFAS-Free Anti-Sticking Coating Used in the Bakery Industry

The S-LCA approach was applied to a novel PFAS-free anti-sticking coating used in the bakery industry (i.e., coating of baking trays and pans) which is compared to a conventional anti-stick coating (Teflon). This innovative coating is produced by Laurentia Technology SLL, which specialises in microencapsulated active ingredients and nano-enabled functional coatings. The material assessed for this case study is a nanocomposite coating composed of silica carbide and titanium dioxide (SiC@TiO_2) which provides non-stick properties when applied in bread baking trays. This innovative material is a substitute for Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS)-based non-stick coatings, such as Teflon (Polytetrafluoroethylene or PTFE). Indeed, it is well known that exposure to high levels of some PFAS may cause adverse health effects including reduced antibody responses to vaccines, increased cholesterol levels, low infant birth weight, and increased risk of high blood pressure [23]. Therefore, industries are currently searching for ways to substitute Teflon-based coatings for safer and more sustainable alternatives.

The opportunity to avoid the use of toxic and carcinogenic substances such as PFAS is a promising step towards safer alternatives to the current market options. The innovative product has been developed using Sol-Gel-Derived Silicon-Containing Hybrids modified with $SiC@TiO_2$ which enhances anti-sticking properties when applied on baking trays. The presence of SiC in the core of the material increases the mechanical and thermal properties, the durability, and improves the anti-sticking properties of the surface on which it is placed. The material main ingredients are two components, a 60 nm $SiC@TiO_2$ and a 500 nm $SiC@TiO_2$.

Along with the safety and environmental impacts [23,24] caused by the production and application of the nanocomposite coating composed of silica carbide and titanium dioxide ($SiC@TiO_2$), the social impacts bring additional insights into the overall sustainability of this material. The assessment of these social impacts is the main aim of this manuscript.

RESULTS

Case Study Goal and Scope

Goal

The system assessed is the innovative anti-sticking nano-enabled coating composed of silica carbide and titanium dioxide ($SiC@TiO_2$) described in section (The case study of a novel PFAS-free anti-sticking coating used in the bakery industry). The obtained results will serve different purposes. First, they contribute to the development of the adopted simplified S-LCA approach through its operationalization; second, they allow the comparison of the innovative coating material to traditional market options; and third, they provide the company Laurentia with important information on possible social sustainability 'hotspots of concern' to support the avoidance of these concerns by e.g., selection of alternative suppliers and/or more socially responsible corporate practices.

Scope

Functional Unit

The functional unit (FU) was defined as the coating of 1 m^2 of an industrial baking tray for five years of its use. This time period corresponds to nine re-coatings of the innovative product and five new Teflon-coated trays. The area of a standard baking tray was estimated based on data collected from main resellers' websites, and the required amount of coating was calculated accordingly. S-LCA practitioners pointed out in few publications that the identification of a FU for social impacts is even more challenging than for environmental impacts. Indeed, when attempting to measure social impacts, finding a suitable unit to convert social into physical flows becomes complex [28,29]. However, according to the UNEP Guidelines [26], it is a mandatory step of performing a S-LCA study. This step is indeed essential to ensure comparability to other studies concerning the same field of application. Moreover, in this case the obtained results should be aligned to the results of environmental LCA and LCC studies performed for the same product, as this study is part of a broader Life Cycle Sustainability Assessment (LCSA). The five-years' time span was decided considering the estimated service life of the innovative coating. In fact, after application on a baking tray, the coating lasts six months but can be re-applied to the same tray several times to achieve an average service life of five years. The coating is designed to be removed from the tray after its service life, as reported by the producing company. In contrast, the Teflon-coated trays have an average service life of eight months, after which the whole tray is disposed of. Detailed data collection is available in Sections 1 and 2 of Supplementary Materials.

System Boundaries

Innovative Product System

This study covers the life cycle from cradle to the use phase. After being sourced in various countries, raw materials are transported to the production facility located in Spain and processed accordingly. Then, after being sold to a third company, the paint is applied on a baking tray. The product system for the innovative coating was modelled based on information retrieved from the production company Laurentia, up to the production life cycle stage. For the use life cycle stage, some assumptions were made concerning the origin and cost of the baking tray, since the company Laurentia could provide data only on the energy requirement for the layering of the coating. It was decided to consider three scenarios to account for geographical diversities of the supply chains. The scenarios are organized as follow: the first scenario considers a tray and a coating process based in China; in the second scenario the same activities are conducted in a facility in the USA; in the third scenario the use phase is completely based in Europe. The end-of-life (EoL) was excluded from the system boundaries as the SHDB available for SimaPro does not include data on the EoL and consumer impacts [30]. Figure 2 shows the life cycle stages included in the system boundaries of the innovative product system. The production includes various phases that were modelled in SimaPro using the SHDB database. Even though the system is usually modelled by production phases, in this case the authors considered it more convenient to have impacts directly related to each raw material (including sourcing and transportation), to highlight the hotspots concerning each supply chain, instead than link it to a production step. The energy required for production was kept separated, to obtain a clearer representation of results. Therefore, results are organized to showcase impacts related to each raw material supply chain and the energy consumption and not impacts related to the life cycle stages.

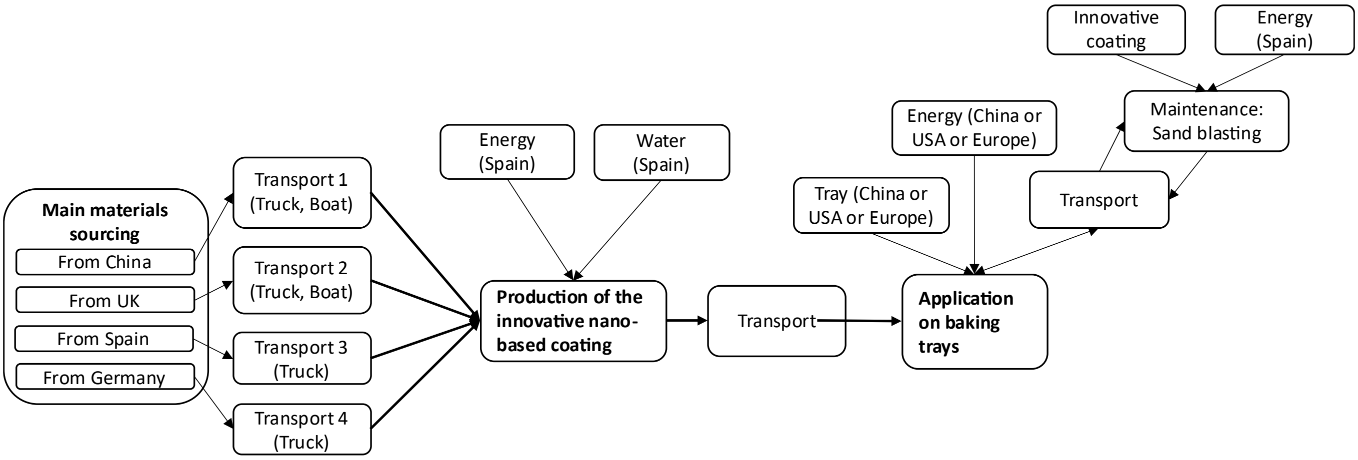

Figure 2. Product system of the innovative AdMa-based anti-stick coating, sourcing, and production.

Benchmark product system

The benchmark material product system is modelled using a set of simplified assumptions and secondary data sources. As for the innovative product, it includes the sourcing of the raw materials, the transportation, the energy required for the production, the production of the tray, and the use phase. However, since the literature data are less specific than the industry-derived information, the benchmark supply chain is quite simplified. The main source of data is the Ecoinvent database for the material and resource quantities (see Table S6). The raw materials are all aggregated under a generic "Teflon" process, while the production life cycle stage consists in one phase including the energy requirements. Concerning the countries of origin for the benchmark product system, it was decided to align with the same three scenarios considered in the innovative product system. More details on the benchmark modelling assumptions, database choices and sources of costs of materials and resources are summarized in Tables S6–S9. Figure 3 shows the life cycle stages included in the system boundaries of the benchmark product system. Because of the lack of available information on the use stage (i.e., the application of the paint on industrial baking trays performed by an external company) for the benchmark, it was assumed that the application of Teflon to the tray requires the same amount of energy indicated by the production company for the innovative coating, making this phase the same for both product systems.

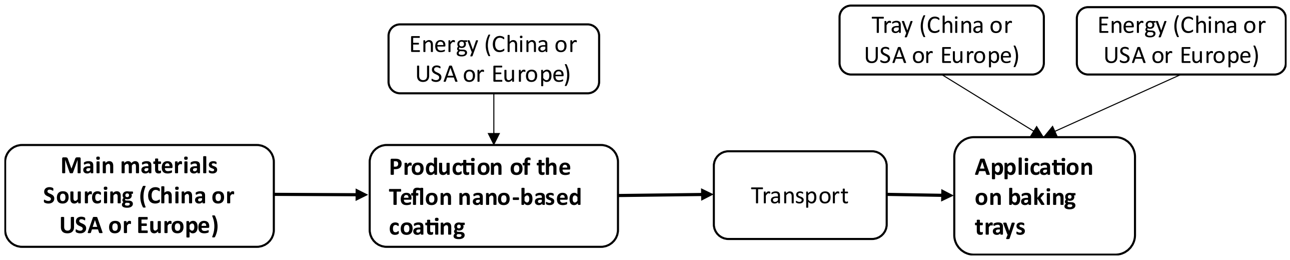

Figure 3. Product system of the benchmark scenarios, with either China, USA, or Europe-based sourcing and production.

Assumptions and limitations

As reported in the previous section, primary cost data for the innovative anti-stick coating were obtained directly from the manufacturing company, while the data for the benchmark were retrieved from the literature. In both cases, data are only quantitative (e.g., kg of raw materials, kWh of energy, liters of water, etc.), while qualitative data such as from stakeholder interviews or surveys was not collected due to the limited time and resources available to the company for the data collection process.

The system boundaries were defined as cradle-to-use, excluding the EoL stage from the assessment. This decision was driven by the lack of data on treatment processes in the SHDB, which does not provide sectoral representations suitable for modelling EoL activities. Although the innovative coating is not expected to alter the EoL treatment route of the tray material itself, the two systems differ substantially in the frequency at which EoL activities occur over the five-year functional unit. The innovative system undergoes EoL treatment at the end of the period, whereas the benchmark system requires full tray replacement approximately every eight months.

Depending on availability of GTAP sectors in the SHDB, some assumptions were made on the life cycle impact assessment phase. Due to the aggregated structure of the SHDB, several input materials were assigned to broad country-level sectors. This aggregation reflects database constraints rather than a claim of technological equivalence or representativeness. For example, both the advanced materials developed for the innovative coating formulation and the benchmark coating were assign to SHDB process “Chemical, rubber, plastic products”, that, besides the limitation introduced above, is already an aggregation of two GTAP sectors (33. Manufacture of chemicals and chemical products, 35. Manufacture of rubber and plastics products). As a consequence, the resulting social impact indicators are primarily driven by country-level risk profiles rather than by material or technology-specific characteristics, particularly for advanced materials for which production routes and occupational practices may differ substantially from sector averages. Moreover, the transportation of the innovative nano-based anti-stick coating main materials to the production site, even if specified by type in the data collection (e.g., truck, boar, air, etc.), could not be associated with database processes specific for means of transportation because the SHDB only provides the general process "transport", by country. The same applies also to the benchmark material for which the means of transport was also not specified.

Case Study Social Life Cycle Inventory

Data sources and collection

The social impacts along the supply chain of the assessed materials are modelled using the SHDB available for SimaPro, where input data on costs and country of origin of main materials, transport, energy, and water consumption inputs are required. Since the SHDB requires inputs in US Dollars 2011, when it was necessary, they were converted to euros with a factor of 1.392 to account for inflation [31]. For the innovative product, site-specific quantitative primary data were collected covering the main material types, the related amounts and costs, the resources required, and the countries of origin. For the benchmark, the same company was asked to perform a desk review on Teflon production countries and costs, which was integrated with the research performed by the authors. The Ecoinvent database was the primary source of quantitative data on mass and energy requirements for the production of Teflon, collected from the processes of Tetrafluoroethylene. For the Europe-based scenario, it was possible to identify the countries involved in the sourcing and the production from the database unit process (i.e., a least disaggregated process, from which it is possible to see how it is built). Therefore, the European countries selected in the SHDB coincide with the inputs included in the Ecoinvent process. Instead, the global Tetrafluoroethylene process used for the China and USA-based scenarios were considered too complex to extract geographical data. Instead, a literature review showed how the production main actors are now located in the Pacific Asia [32]. Therefore, for the first scenario the SHDB processes were selected from China. For the second, it was chosen to use SHDB processes from USA. This decision was due to the fact that the United States of America are reported to be the country were most of the major Teflon industries were born, even though in the recent years production has been shifted to Asia [33]. Indeed, even though it used to be a business with legal address and production plants based in America, it followed the main trend of delocalizing its production, due to the more convenient labour and legal conditions. Nonetheless, the USA scenario was considered relevant, representing an opportunity to highlight possible recent changes in the potential social impacts due to relocation.

The information on the gathered prices reflects the present situation of the market and social condition, for which the model cannot include forecast on their development. However, it is reasonable to assume that trade patterns and social condition worldwide will not change in a short period of time [18].

Impact subcategories and inventory indicators

The selection of subcategories and inventory indicators relies on the selection of the SHDB as described in the Methods section (see Section Life Cycle Inventory). Therefore, the data on the cost for each material, transportation, and resource use, collected for the innovative product system and the benchmark product system scenarios were elaborated and assessed for all subcategories through the indicators pertaining to each specific impact subcategory, according to the Social Hotspot Index method.

Case Study Life Cycle Impact Assessment

This study is a one-step social risk hotspot assessment performed with the Social Hotspot index reference scale impact assessment method, provided within the SHDB for the software SimaPro as described in the Methods section (see section (Life Cycle Impact Assessment)). Therefore, the impacts of the innovative and the benchmark product systems are related to the social performances or risks associated with each impact subcategory, as a measure of the likelihood, for each product scenarios, of a social risk to happen. The innovative product system scenarios are compared to their relative benchmark system scenarios (i.e., same geographic locations are compared), where the potential social risk is aggregated in one score for each scenario, for the sake of comparison. However, to better understand the social risks hidden along the supply chain, the LCIA was performed to assess the comparison between the two coatings only (i.e., innovative nano-enabled coating and Teflon) and for the innovative coating alone. In this way it was possible to disaggregate the potential social risk score of the comparison, highlight the most critical materials included in the production of the nano-enabled coating, and develop the interpretation with different level of complexity.

Case Study Results Interpretation

In the following paragraphs the results of the S-LCA are presented focusing on three different scales corresponding to the whole product system or parts of it. The results presented in this section reflect potential social risk hotspots associated with country and sector-level data from the SHDB, rather than material, process, or company-specific social performance. Consequently, reported mrheq values represent potential social risk exposure rather than actual social performance, as they are calculated by combining activity levels (working hours) with country- and sector-specific risk characterization factors embedded in the SHDB. The aggregated category scores should be interpreted as indicators of relative risk intensity across scenarios.

In section (Comparison of life cycles), the product system is considered from cradle to the use phase, highlighting the avoided impacts due to an improved functionality of the product incorporating the nano-based material. In section (Comparison of the coatings), the comparison the two coatings are presented, leaving the use phase out of the system boundaries which is strongly affected by the high contribution of the tray to the overall impacts as a result of its high weight and costs in comparison to the other materials. Finally, in section (Focus: the innovative nano-enabled coating production) the assessment focuses on the innovative coating, to allow the identification of social hotspots in a part of the value chain for which the production company can implement improvements.

Comparison of life cycles

Results shown in Figure 4 presents, at the level of categories, the comparison between the life cycle of the tray incorporating the innovative anti-stick coating and the benchmark, according to the three scenarios (i.e., China, USA, Europe). The aggregation in categories allows to better display the results of the comparison, at which this section is aimed. Data disaggregated at the subcategory level are provided in Section 3 of Supplementary Material. The innovative material product is associate with lower potential social risk in comparison to the benchmark, in all cases. The benchmarks account for higher potential social impacts compared to the respective innovative coating product system in all scenarios, partly due to the impossibility to reapply the Teflon coating on an existing tray. However, the USA and Europe-based benchmarks have lower social impacts compared to the innovative material applied to a Chinese tray, reflecting the different country-level risk profiles. It should be noted that the lower mrheq values observed for the innovative tray over the five-year functional unit are primarily driven by reduced upstream production activity resulting from lower tray replacement frequency, rather than by an intrinsically lower social risk intensity of the coating itself.

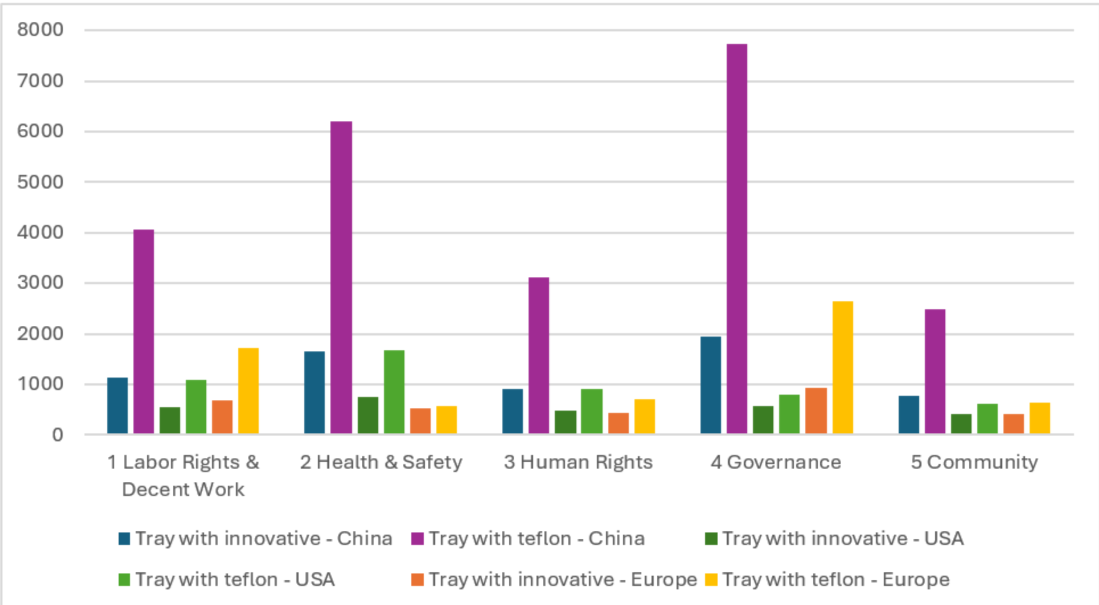

Figure 4. Categories weighting results for the comparison between the 5y life cycle of the tray incorporating the innovative anti-stick coating and the benchmark, according to the three scenarios.

Comparison of the coatings

As in the section above, the results are presented at the level of categories, suited for the objective of comparison (Figure 5). Data disaggregated at the subcategory level are provided in Section 4 of Supplementary Material. The innovative coating is compared with the benchmark coating, again considering the three geographies for the sourcing of the raw materials. The innovative coating has lower potential social impact only compared to the China-based scenario, while it has higher *mrheq* than the USA and Europe-based scenarios. Indeed, the innovative material includes raw materials sourced from different countries among which is China, which contributes significantly to the overall potential impact. This results in an overall higher potential social impact for the innovative coating supply chain, which includes raw materials from countries associated with higher social risk values. The EU and USA based supply chains, on the other hand, reflect the greater transparency and availability of data supporting lower social risk levels for the SHDB and thus resulting in lower potential social impacts. Accordingly, the observed differences should be interpreted mainly as variations in potential social risk associated with geographic sourcing profiles, while the role of technological innovation remains secondary. The most impacted categories are governance and health and safety.

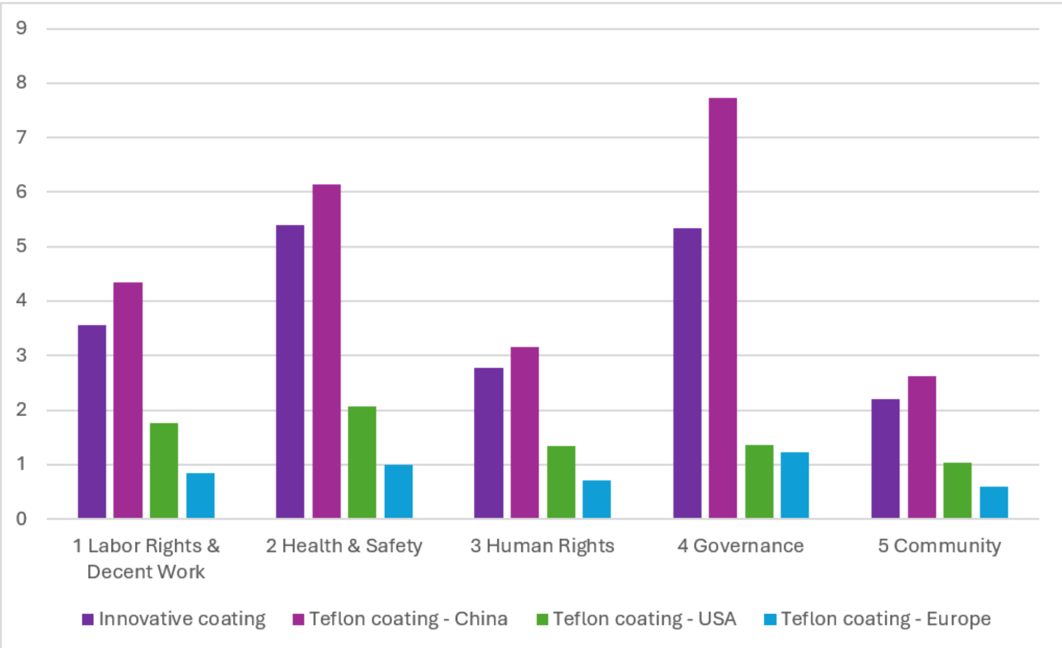

Figure 5. Categories weighting results for the comparison of the innovative coating with the benchmark coating, according to the three scenarios (China, USA, and Europe based product systems).

Focus: the innovative nano-enabled coating production

Results shown in Figure 6 present, at the level of subcategories, the potential social impacts associated with the innovative anti-stick coating production. This focus allows to appreciate which raw materials are associated with the highest share of mrheq. Indeed, since the details of the innovative coating composition are lost in a comparative or life cycle study, this focus provides with the opportunity to investigate those steps of the supply chain more likely to be tackled. The aggregation at the level of subcategory was preferred to support the interpretation of the social hotspots of the innovative coating value chain. Results at the level of categories are available in Section 5 of the Supplementary Material. The results indicate which materials' supply chains should be further investigated, or which subcategories/social issues are related to the highest number of mrheq along the life cycle of the materials. Within the adopted screening-level S-LCA, sourcing geography represents the dominant driver of differences in potential social risk, while process-specific characteristics play a minor role. Freedom of association, occupational toxicity and hazard, and high conflict zones are the subcategories with higher potential social risks associated. Results for the innovative coating show a predominance of three raw materials on the social hotspots quantification, those being the silica carbide 60nm, the silica carbide 500nm, and silicone, for all the subcategories and categories. Indeed, the silica carbides are the only raw materials imported from China, which, as seen, contributed significantly to all cases. These findings were presented and discussed during a workshop organised with experts from the company producing the novel PFAS-free anti-sticking coating and S-LCA experts. The main goal of the workshop was to identify the best strategy for validating of the S-LCA results. The outcomes highlighted the need to conduct a desk review and a survey to better assess the sustainability performance of the raw materials suppliers. Accordingly, an approach to refine results was followed, starting with a desk review of the supply chains of the raw materials that contribute most to the potential social risks. In the case of silicone, sustainability reports of the supplier helped to lower the risk levels. The company has a comprehensive sustainability section published on the website, covering all social themes relevant for the assessment. A qualitative comparison between the potential social risks identified through the SHDB-based assessment and the sustainability information disclosed by the company suggests that the actual social risks in the current supply chain are likely lower than those represented by the database-derived country-sector risk profiles. In the case of silica carbides, since reports were found only at the country sector level, a survey was deemed necessary. The process of constructing the survey and the survey shared with supplier can be found in the Section 6 of Supplementary Material. However, the supplier did not respond and therefore the social risks identified could not be compared with actual conditions. Consequently, the company used social hotspots results, reflecting potential risks, as a qualitative decision-support input to guide a further supplier selection, considering a broader pool of suppliers aligning with their transparency efforts.

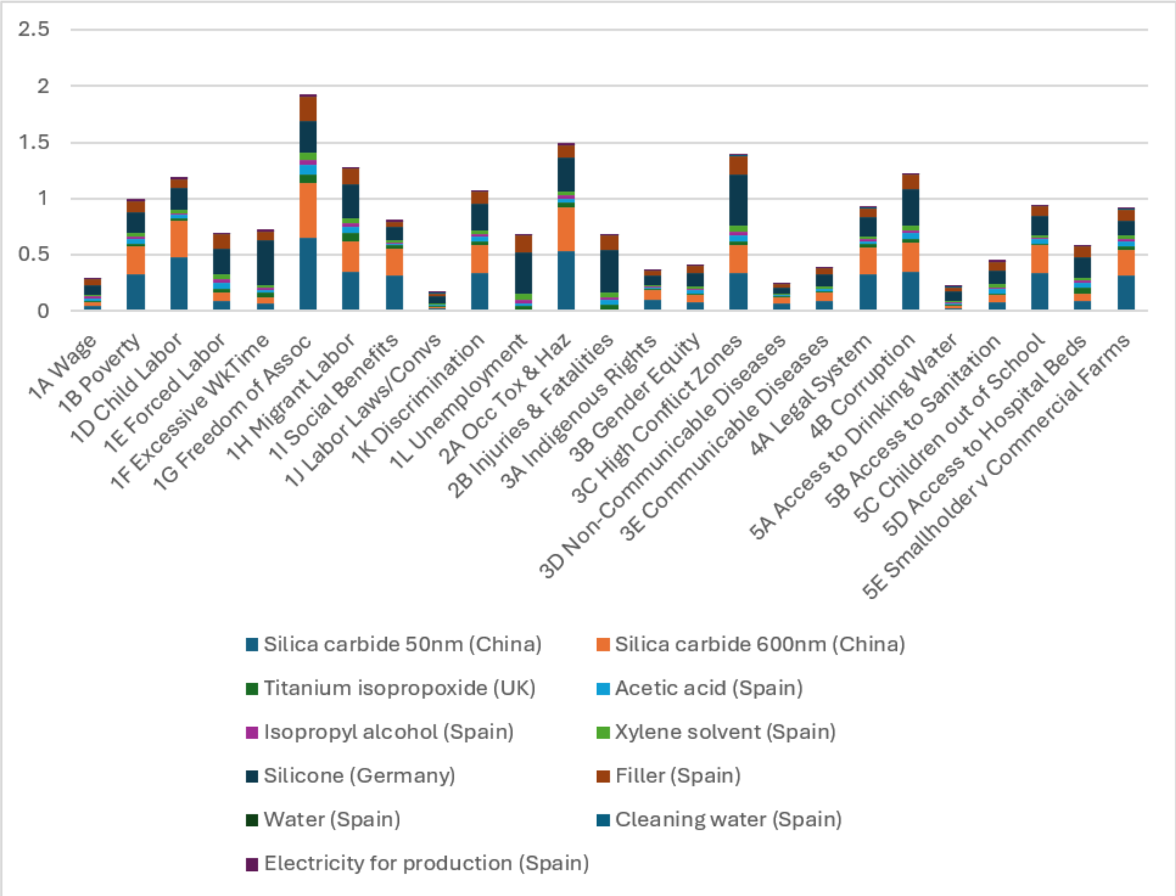

Figure 6. Subcategory weighting results for the innovative coating raw materials and resources.

DISCUSSION

The results indicate that, overall, the product system incorporating the innovative nano-enabled anti-sticking coating potentially has lower social impacts along its value chain, compared to the Teflon-based coating. The compared systems differ both for country-level risk profiles and for their life cycles, considering the re-applicability feature of the coating of the innovative product system. The S-LCA study results were obtained at subcategories and categories levels, providing a good overview of the potential social risks caused by different geographic scenarios pertaining to the innovative material and the benchmark. The assessment was conducted by comparing a tray coated with the innovative nano-enabled anti-sticking coating and recoated periodically for a total of nine times and five trays coated with Teflon, both accounting for a five-year time span. Although the functional unit ensures comparability in terms of delivered service, differences in service life and reuse patterns between the innovative and benchmark systems have relevant implications for social comparability. However, due to the exclusion of end-of-life processes, reflecting current limitations of the SHDB, these differences are captured primarily through variations in material demand and production frequency, rather than through differentiated end-of-life pathways. As a consequence, the comparative results reflect potential social risk exposure associated with production and use stages over the defined functional unit, while social impacts related to disposal or recycling are not represented. To overcome this limitation and improve the comparative outcomes, also the production of the two coatings only (i.e., the nano-enabled anti-stick coating and the Teflon coating) was assessed. Finally, a specific focus was provided for the innovative coating system only (i.e., the nano-enabled anti-stick coating) to assess what raw materials are associated with the highest potential social risks. The results showed that, in the first case, the life cycle of the innovative product system has lower potential social risks than the benchmark, for all the scenarios (i.e., China, USA, Europe). When comparing the production of the coatings, the innovative product system lowers the social risk only compared to the China option, while it has higher potential impacts compared to the Europe and USA options. These results are primarily driven by the country of origin of the raw materials, which strongly affects the associated social risk levels, particularly in the case of China. In contrast, differences in tray replacement or reuse frequency have a much smaller influence on the overall comparative results, as illustrated by the lower impact of the Europe and the USA product system relative to the innovative product system in the China scenario. Potential improvements of the social impacts associated with the replacement of the innovative coating can be observed when comparing products within the same country scenario. Therefore, while the assessment captures real supply-chain characteristics through country-level risk factors, the effect of reuse frequency plays a secondary role in shaping the overall comparative outcomes.

Supply Chain

This result is strictly linked with the transparency of the supply chain, which is crucial to avoid high risk level of social impacts. The innovative nano-enabled anti-sticking coating is produced using, among others, raw materials sourced from China, that significantly increase the potential social risks because of the data availability and quality included in the database at the country level. Country statistics, intergovernmental databases, NGO reports, and academic literature are integrated and selected based on a set of criteria and the precautionary principle. A lack of data or transparency might significantly raise the risk level attributed to the assessed sector for a specific country. The results showed that three of the raw materials are mostly responsible of the potential social impacts along the life cycle of the innovative anti-sticking coating, those being silica carbide 50 nm (origin: China), silica carbide 600 nm (origin: China), and silicone (origin: Germany). Based on the main affected categories (i.e., Health and Safety and Governance), the stakeholder categories most impacted were workers and local communities. Such results highlight how the activities carried out in the sourcing of the materials, and in minor part in their transportation, accumulate the highest probability of adverse situations to happen for the assessed stakeholder groups. To verify if these results correspond to actual impacts, we carried out a screening literature review and then developed a survey to be submitted to the suppliers. We acknowledge that this procedure accounts only for the answer of one stakeholder (i.e., the supplier) and is less representative than involving the workers and local communities of the area where the raw materials are produced. This further involvement, however, requires significant resources and budget allocation, which might make it unfeasible. Moreover, companies might fear consequences from the suppliers if they implement these involvement activities, as suppliers might consider the practice too invasive. This should not stop practitioners to look for primary data, but it has to be considered as a limiting factor. On the other hand, desk reviews are easier to manage, but results from these sources might be hard to find or are often not accessible. Moreover, while being less invasive for the companies it might as well either not provide enough data or require excessive research time from the practitioners, contradicting the reasons it might be preferred in the first place. Concerning the supply chain of silica carbides, we found in literature that the Chinese mining industry is reported to deeply affect the structure and conditions of surrounding communities, on various levels. While allowing wealthy groups to thrive in the resource extraction collateral markets (such as transportation, maintenance, etc.), the industrial sector negatively impacts more vulnerable social groups. Endangered health conditions, increased poverty due to the lack of good institutions, exacerbated inequalities are some of the issues faced by communities surrounding extraction sites. On a positive note, it seems that improved infrastructure due to industrial development, like clean water and improved transport connection can be identified as positive impacts of mining activities [34]. These literature findings correspond with the results of the S-LCA, supporting the social hotspots identified (e.g., occupational toxicity and hazard) and the low-risk areas resulting from the assessment (e.g., access to clean water). These considerations could not be mitigated using primary data from the Chinese suppliers. As a first step, the authors checked if corporative social responsibility reports were available on the company website but did not find any reference neither to social sustainability neither to sustainability in general. Therefore, we develop a short and user-friendly questionnaire covering the subcategories associated with a score higher then 1pt, to check which social risk could correspond to actual impacts. The company producing the novel PFAS-free anti-sticking coating used in the bakery industry agreed to send the questionnaire to their Chinese suppliers, which was provided as an online form. As we did not receive any response, the results could not be complemented by primary data. On the other hand, it was possible to check the social risks associated with the German supplier against their publicly available sustainability reports. This allowed to assess that the potential social impacts resulting from the SHDB were prevented by the company's initiatives.

Improvement Strategies

It is not always possible to collect primary social data. It is therefore responsibility of the companies setting stricter criteria when constructing or reassessing their supply chain. Awareness on suppliers' performance on sustainability issues is key to mitigating social risks in countries where laws and regulations do not guarantee the enforcement of adequate environmental and social compliance policies. Indeed, the EU is trying to solve this matter with the Corporate Sustainability Reporting Directive (CSRD) [35], making it mandatory also for non-EU companies trading with EU, under certain conditions, to report according to the European Sustainability Reporting Standard. CRSD will become mandatory in 2028 for non-EU companies involved. Until then, preferring supplier able to provide transparent reports, especially until the data availability and sector coverage of databases for S-LCA would be adequate to reflect the complexity of the world dynamics, is currently the strongest action a company can undertake to improve the social risk level associated with its value chain. Indeed, the company involved in our case study, after receiving the results, started to look for suppliers' alternatives more transparent on their sustainability priorities.

While many social hotspots could not identify actual social impacts, more information about the suppliers would substantially reduce the uncertainty on the real existence of the identified potential social risks. It is important to stress that reliance on primary data provided by manufactures and material providers, rather than databases, can provide more accurate results. Therefore, a recommendation for a more robust S-LCA would be for manufactures to engage with their suppliers in order to obtain more realistic results. This could include a more selective selection process, by raising the transparency requirement for the company supplier, requesting to provide social sustainability reports to show their efforts. Moreover, ensuring their supply chain is transparent and traceable, could improve the competitiveness of the company on the market. In addition, such an engagement resonates with the SSbD approach with a focus on the social dimension.

Opportunities and Limitations

The application of S-LCA to support the operationalisation of the Step 5 of the SSbD framework presents significant opportunities to generate suitable results that are useful for designing and further developing more socially sustainable innovative materials. The assessment helps companies to identify in an easy and feasible way which social risk hotspots could be associated with their supply chain and act against them while the product development is still ongoing and therefore the implementation of changes comes at a lower price. The SUNSHINE/SUNRISE approach aims to trigger stakeholder discussion, prioritize supply-chain transparency efforts, and identify areas where additional supplier engagement or data collection would be required in subsequent development phases without setting quantitative social risk thresholds, as the assessment is targeted to innovation at rather low technology readiness level. The main result is engaging companies in the process and raising awareness on social issues associated with their products, by sharing the methods and results while they are used/produced. In this case study, regular meetings were held since the data collection phase up to the presentation of the findings. It followed a discussion where the company acknowledged the importance of traceability of the supply chain. It is important to stress that these results are strongly influenced by the level of development and coverage of the databases used in the S-LCA assessment (as in this case the SHDB), which opens the debate of the opportunities and challenges of being able to produce results at the level of detail and certainty desired by decision makers. Indeed, the SHDB uses available average data at the country level, while social risks may vary significantly at the company's level [18]. Moreover, the database covers few types of processes, limiting the results specificity at broad sectors level. This limits the ability of the assessment to capture differences related to production scale, technological sophistication, or specific occupational health and safety practices associated with advanced materials. Specifically, the currently limited number of database processes still does not allow to account for the complexity of the product systems addressed in this study, since many raw materials involved in the coating production had to be associated with the same database process. Similarly, all transportation types are represented by a single generic "transport" process, reflecting the aggregated coverage of the database. This does not account for the specific worker-related social risks associated with different transportation modes or routes. Transport-related impact should be interpreted as indicative of general trends rather than precise hotspot locations. This issue was found also in a similar study by [18], where the social risk could be allocated to wide market sectors, losing the details on the microscale. To face this limitation, in this study we are considering as benchmark a sourcing and production completely based in countries associated with different risk levels. This way it is possible to point out significant differences of the assessed alternatives in terms of the potential social risk, mainly due to their country of origin, when the detail at the sector level is constrained by the database. Results related to aggregated sectors should be interpreted as indicative of potential social risks associated with the geographical context of production, rather than as precise representations of the social performance of the specific materials considered. Visentin et al. [17] pointed out how results can be very similar for countries with comparable social issues. In our case, the comparative S-LCA of the coatings only, show that the nano-enabled material offers a better scenario in terms of social impacts when compared to a benchmark completely sourced in China, but not for the Europe and USA based scenarios. However, due to the lack of primary or database data on the benchmark, it was necessary to make a set of assumptions to model the product system with Teflon, thus increasing the level of uncertainty. Moreover, the comparative nature of LCA is not easily applicable to social impact assessment. This is because the intrinsic nature of social matters does not reason well with comparison, since the only fact of a social risk to take place, it is to be considered a negative outcome which cannot be offset with positive impacts. In fact, assessing 'hotspots of concern' rather than comparing scenarios might provide better insight into the location of social risks along the supply chain of the investigated product systems. This was assessed in the last part of the S-LCA study where the potential social impacts associated to the raw materials used to produce the nano-enabled anti-stick coating was deeply investigated. These S-LCA results allow to appreciate the difference on the average declared corporate social responsibility that differs based on the country and the sector, requiring companies to mitigate the social risks by either ask for sustainability reports to their suppliers or to consider new economic partners. Indeed, having suppliers committed to corporate social responsibility can strengthen the transition to safe and sustainable technologies, guaranteeing that also the downstream of the life cycle is engaging in the sustainability effort. Companies emerging in the AdMa context would benefit in having integrated sustainability strategy in their business models, as the trend in investors preferences is strongly oriented to sustainable businesses [27].

Moreover, a better knowledge of the context from which the raw materials are sourced would allow to collect further data to assess positive impacts, since it would highlight the positive outcomes of the innovative AdMa-based product. This would not serve the purpose of identifying trade-offs, as explained above, but provide a more comprehensive understanding of the context. Indeed, the SHDB method available for SimaPro only allows the assessment of impacts with a negative connotation, in an Environmental LCA fashion. Only the updated version of the SHDB method includes the first subcategory assessing positive impacts, "socioeconomic contribution" [27]. Positive impacts are more easily retrievable from qualitative data, which might highlight how the presence of the extraction or the transport companies on the territory affects employment rates by asking people directly or by consulting the organisations documents. This would be an example of positive social impact caused by the only presence of the product or the company in a specific territory (positive social impact called Type B). Type C positive impacts, due to product utility, might be found investigating the technological development that the innovative product would provide due to its intrinsic properties. There is one additional type of positive impacts, or Type A, that accounts for Actions and practices going beyond the minimum requirements, that by producing a positive impact on the society at all stakeholders' level ensures improved condition and healthy working environment [26]. The latter is not applicable in the specific study.

Regarding the system boundaries, the exclusion of the EoL phase due to absence of data in the SHDB might have limited the extent to which differences between the two systems could be captured. In particular, the innovative coating can be re-applied on existing trays after sandblasting, and it is designed to last on average five years, whereas conventional Teflon-based trays are fully disposed of approximately every eight months. A differentiated assessment of the social impacts associated with the two distinct EoL pathways could further influence the comparative results. As a consequence, the results should be interpreted as a comparative assessment limited to the modelled life cycle phases. While the EoL represents a socially relevant phase, its exclusion reflects a recognized limitation of current S-LCA databases.

Uncertainty and Robustness

While quantitative uncertainty and sensitivity analyses were not conducted, the comparative results are expected to be robust with respect to the main trends, as evidenced by the scenario comparisons (China, USA, Europe). The relative ranking among alternatives is therefore more informative rather than absolute impact values. Geographic assumptions are the major influence on the magnitude of potential social impacts, particularly for materials sourced from high-risk regions, while changes in product replacement frequency play a minor role. In addition to geographic assumptions, structural modelling choices may also influence the magnitude of identified social hotspots. In particular, the assignment of advanced materials to the aggregated SHDB sector “Chemical, rubber, plastic products” and the representation of all transportation activities through a single generic “Transport” process introduce simplifications that may not fully capture technology-specific labour intensity or transport-mode-dependent risk exposure. However, given the screening nature of the assessment and the dominant influence of country-level risk coefficients embedded in the SHDB, such structural simplifications are expected to have a limited effect on the relative ranking of scenarios and on the identification of the main hotspot categories. Therefore, the results should be interpreted as representing indicative comparative trends of potential social risks rather than precisely describing the product systems.

CONCLUSIONS AND RECOMMENDATIONS

This paper presented the results of a comparative S-LCA analysis of an innovative PFAS-free anti-stick coating used in the bakery industry versus Teflon. The S-LCA study both (1) compared the social sustainability performance of the innovative material against the benchmark (Teflon), and (2) identified its potential social hotspots, providing results that can fuel further discussions on the role of simplified S-LCA in the development of emerging materials. It is important to stress that the present S-LCA represents one part of a broader sustainability assessment of the investigated product, which also includes a qualitative sustainability assessment and an LCA and LCC [24]. Together, these complementary analyses aim to support more informed decision-making by providing an integrated evaluation of environmental, social, and economic aspects. To date, the work done on S-LCA in the area of emerging materials is still very limited and with few practical examples. The further development of the S-LCA methodology holds promise to substantially support the development of more socially sustainable advanced materials by providing essential information to the innovators and raising awareness on social risks already at the early R&D stages of innovation and at low TRLs when more opportunities exist for adjustments of the value chain. We believe that this is key to ensuring the sustainability of the new materials/products at optimal R&D costs for industry. The results obtained show how a simplified S-LCA can play a significant role in guiding the development of a new product, by pointing out the criticalities that a non-thorough selection of suppliers and inadequate engagement with the companies providing raw materials might overlook. The operationalization of S-LCA and the lessons learned from case studies can help to overcome some of the current limitations of the methodology and make it a more powerful tool for SSbD.

The authors outlined a few of such limitations in conducting S-LCA, which are suggested areas for further research and methodological development. Firstly, the limited availability of GTAP sectors, especially those covering nano-enabled products, makes the model of main materials in the SHDB less accurate. These could be improved in the next versions of the database, where is envisioned that more GTAP sectors will be included. Future research should aim to integrate more disaggregated social datasets to address, for example, EoL and transport processes, in order to further reduce uncertainty and enhance the robustness of S-LCA results. Secondly, since relying on primary data such as qualitative interviews can be costly and time consuming, to overcome this limitation for both practitioners and companies commissioning a study, it is suggested to verify firsthand whether a sustainability report from the suppliers is available, as it can provide significant support in structuring the hotspots assessment. Until the CRSD is effective for all non-EU companies, this could be a driver to prioritize more sustainable trade relations and provide companies with a market advantage in the European context, where sustainability issues are increasingly valued. Furthermore, a comparative approach can offer valuable insights into preferred choices for supply chains; however, it also raises important questions about the role of relative sustainability in social contexts. While a comparative (environmental) LCA can yield positive outcomes by demonstrating reduced impacts per functional unit compared to a benchmark (i.e., eco-efficiency), this logic does not necessarily apply to social dimensions. In the case of social impacts, achieving a reduction relative to a reference point may not be sufficient to constitute a desirable outcome. Social risks should be minimized regardless of the benchmark, as the presence of any social harm in the supply chain—even if comparatively lower—remains problematic. This line of reasoning highlights the need for further discussion on the role of S-LCA within the broader context of sustainability assessments. On a final note, it is clear how the lack of data and more in-depth empirical expertise in the S-LCA is one of the main obstacles for practitioners to improve the quality of results. Therefore, its increasing implementation in the following years, fostered by the recent release of the updated guidelines and SHDB and the publication of the ISO standard [15], would help to create a stronger bases for future studies pointing towards a better social sustainability profile design.

SUPPLEMENTARY MATERIALS

The following supplementary materials are available online, Table S1: Raw materials to produce the innovative coating, Table S2: Energy requirement to produce the innovative coating, Table S3: Transports to source the raw materials used to produce the innovative coating, Table S4: Resources requirements to produce the tray covered by the innovative coating, Table S5: Resources requirements to maintain the tray covered by the innovative coating, Table S6: Main modelling assumptions for the benchmark system, Table S7: Reference process to model the benchmark coating: Tetrafluoroethylene {RoW}|tetrafluoroethylene production|Cut-off, U (Ecoinvent V3.12, Table S8: Resource requirements to produce the benchmark material, Table S9: Sources of materials and resources' costs. Figure S1: Subcategories weighting results for the comparison between the 5y life cycle of the tray incorporating the innovative anti-stick coating and the benchmark, according to the three geographies, Figure S2: Subcategories weighting results for the comparison of the innovative coating with the benchmark coating, according to the three scenarios, Figure S3: Category weighting results for the innovative coating raw materials and resources. Survey to the suppliers.

DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

SD: Conceptualization; Data curation; Methodology; Writing–Original Draft; Writing–Review & Editing. LP: Conceptualization; Project administration; Supervision; Writing–Review & Editing. AL: Conceptualization; Writing–Review & Editing. AZ: Conceptualization; Formal analysis; Supervision; Writing–Review & Editing. SS: Methodology; Writing–Review & Editing. ML-T: Resources, Writing–Review & Editing. ES: Supervision; Writing–Review & Editing. DB: Supervision; Writing–Review & Editing. DH: Funding acquisition; Supervision; Writing–Review & Editing.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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