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Release Assessment Methodology for Safe Sustainable and Recyclable by-Design Practices for Plastics: The Epoxy-Resin Composite Case Study

Virginia Cazzagon [1], Patrizia Marie Schmidt [2], Bastien Pellegrin [3], Herve Fontaine [3], Delphine Tissier [4], Arrate Huegun [5], Valeria Berner [6], Carl-Christoph Höhne [6], Sebastien Artous [3], Socorro Vazquez-Campos [1] and Camilla Delpivo [1,*]

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Abstract

The development of new chemicals and materials that are inherently safe and sustainable throughout their entire life cycle has become a critical objective in the context of the green transition. This challenge is especially significant for plastics, which often contain complex mixtures of chemicals that may be released during various stages of their life cycle, from manufacturing to use and end-of-life management. Such releases can pose risks to human health and the environment. Within this context, the Safe and Sustainable by Design (SSbD) framework was followed to support the design of an innovative epoxy-vitrimer composite that integrates non-releasable fire-retardant functionalities, aiming to produce a safer, recyclable materials suitable for railway applications. This study presents the identification and quantification of potential releases as part of Steps 2 and 3 of the SSbD framework. A dedicated methodology was established to evaluate the potential release of materials such as flame retardants, non-intentionally added substances, and microplastics throughout the product's life cycle. A systematic template was developed to identify release hotspots potentially affecting workers, consumers, and environmental species and organisms. Based on these findings, experimental simulations were conducted to compare release profiles between a benchmark and the SSbD alternative.

Keywords: release assessment; safe and sustainable by design; plastics; composite; microplastics; nanoplastics; environmental risk assessment; substances of concern; emerging pollutants

1. Introduction

During the last years, a lot of effort has been made to implement the Safe and Sustainable by Design (SSbD) Framework developed by the European Commission (EC) Joint Research Centre (JRC) [1], where the definition of criteria and evaluation procedure for chemicals [2], the application of SSbD framework to case studies [3] and the SSbD methodological guidance [4] still lacks of specific methodologies to assess releases along the life cycle of the product development. The use of standardised and reliable communication tools should be further investigated to improve/overcome data and information gaps [5]. Moreover, the application of SSbD in real production contexts is still a key point for the refinement of the Framework, as guidance on how and when to apply existing methodologies as well as assessment tools are needed for pragmatic and flexible SSbD implementation [6]. High attention is paid in the context of plastic production, where plastic contamination is a key point in the current EU regulations such as the Zero Pollution Action Plan and the EU Circular Economy Action Plan. Indeed, over the past twenty years, even more advanced investigations were conducted about the widespread presence and unintentional release in the environment of unreacted starting substances, residual processing aids, impurities and reaction by-products with a specific focus on substances of concerns, such as microplastics, generated from the degradation of plastic products [7–11]. As a result, in October 2023, an EU regulation under REACH was published that restricts the sale of primary microplastics, both as standalone substances and as intentionally added components to products, the EC 2023/2055 [12]. Regulation of unintentionally released secondary micro- and nanoplastics (MNPs) is not yet established, but it may become increasingly important with the introduction of the Ecodesign for Sustainable Products Regulation. Understanding the release of microplastics along a product's lifecycle allows designers and manufacturers to reduce release at the source through material selection, product design and process changes. Accurate data on release rates and mechanisms are also essential for risk assessment, regulation and for prioritising interventions that protect ecosystems and human health. Moreover, quantifying secondary microplastic emissions helps ensure that circular-economy measures (e.g., recycling, reuse) do not unintentionally increase microplastic pollution, enabling more genuinely sustainable product systems.

For this reason, in the Horizon Europe SURPASS project, a Safe, Sustainable and Recyclable by Design integrated approach has been developed and tested in three composite materials case studies, representing three key market sectors: construction, automotive and packaging. How the SSRbD approach has been made and tested in case studies through an interdisciplinary group of experts is presented in Soeteman-Hernandez et al. 2025 [13] where a tailor-made guidance for identifying polymer material relevant information is described.

However, while the hazard assessment as Step 1 of the JRC SSbD framework is operational and well-structured through the H classification, methodologies to easy identify hotspots of released materials and transformed substances at the early stage of the product development are missing, especially for complex materials such as plastics and their composites, where many different species can be released along the product's life cycle. This represents a critical gap, since without robust approaches to anticipate where and how release/ emissions may occur along the life cycle, it is difficult to implement (re)design measures, compare alternative materials and production routes or assess the safety of emitted substances for workers, consumers and the environment.

For this reason, in the current work, a methodology to assess release of materials to support the Step 2 and 3 of the SSbD Framework implementation for composite materials is presented. Moreover, we demonstrate its implementation in a real case study: an epoxy-resin composite material containing halogen-based flame retardants to be potentially used as exterior part of a train. The assessment started with the identification of material release hotspots along the lifecycle. For this purpose, a template based on ECHA guidance and scientific publications was developed to collect key information on substances and activities at each lifecycle stage, drawing mainly on expert knowledge. A traffic-light classification was then applied to flag potential release hotspots. Next, actual releases at those hotspots were quantified experimentally by simulating the relevant activities. Finally, a scoring-system was developed and applied to determine whether the SSRbD alternative achieved improved release performance compared with the reference material and reported in Artous et al. submitted [14].

2. Materials and Methods

2.1. Case Study Description

To increase safety, sustainability and recyclability performances of the metal material to be used in exterior structural part of a train, different SSRbD strategies were selected and implemented. The replacement of a metal material with a plastic composite one would allow a significant reduction in

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vehicle weight and, thus, energy consumption during its use. Moreover, the use of non-halogenated flame retardants (FR) contributes to the improvement of human health and environmental safety.

Figure 1 shows the starting point used in this case study (Reference route) in which the metal part is expected to be substituted by a light-weight material in order to decrease energy consumption during use in railway application and recycling at the end of life. A promising alternative emerging in the last year is represented by the Safe and Sustainable by Design route (indicated here after as SSbD#0) using a lightweight material (carbon fibre epoxy composite), which is however not recyclable and contains a halogen-based FR. To go further, a halogen-free FR is used, combined with a reversible hardening technology, where the infusion manufacturing process permits to develop a recyclable composite, thus increasing the performance in terms of safety and sustainability (indicated here after as SSbD#1 route). To investigate release performances of the different SSbD implemented strategies, SSbD#0 and SSbD#1 have been tested.

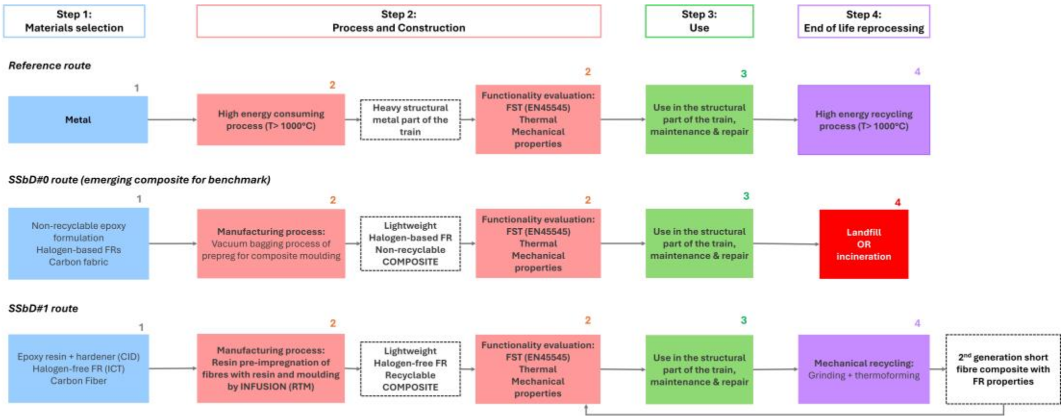

Figure 1. Reference and SSbD routes (SSb#0 and SSbD#1).

The SSbD#0 route is represented by a composite containing the halogen-based FR Tris(1-chloro-2-propyl) phosphate (TCPP) (i.e., Araldite LY1564 and TCPP). The composite material representing SSbD#1 route is SP3 RTM which is made by a flame-retardant epoxy resin (i.e., Araldite LY1564 and Exolit EP360, respectively) and carbon fibers. Both composites were fabricated through resin transfer manufacturing process. To investigate the contribution also of carbon fibres in the material release during simulated exposure scenarios of SP3 RTM, composite without carbon fibres were also tested (indicated as SP3). All the details related to the chemistry behind the tested materials are described in Berner et al., 2025 [15].

2.2. Release Assessment Methodology

Within the SSbD framework, hazard assessment is a well-established procedure in Step 1, but the absence of systematic methods to identify and quantify material releases across the life cycle hampers reliable exposure and risk assessment for workers, consumers, and the environment.

The first step towards the assessment of potential exposure of substances released from plastics for workers, consumers, or the environment is the identification of release of materials as it refers to the discharge of a material/product during a natural or technical process at any stage of the product's life cycle [16–18]. For exposure to occur, the released materials must be emitted into an environmental compartment where they can undergo fate and transformation processes (transmission) before coming into contact with, and potentially entering the body of the receptor(s) through a specific exposure route [19–21].

For this reason, the proposed methodology focuses on release and it is based on i) the release hotspots identification, ii) quantification of actual released materials through experimental work when a hotspot of release is identified, iii) a scoring system strategy to verify if the SSbD alternative has better performance in terms of release than the reference material, which is included in Artous et al. submitted [14].

2.3. Release Hotspots Identification and Quantification

To identify potential release of substances/materials along the life cycle of each case study (from the manufacturing to the end-of-life, and eventually considering re-use), knowledge acquired in previous projects as well as scientific publications dealing with the identification of hotspots of release were considered, such as the work performed in screening safety assessment in [22–24] or the investigations related to transformation processes included in [25–27]. From this information and considering European Chemicals Agency (ECHA) guidelines such as material-specific information and use-description following ECHA R12:2015 [28], ECHA R14:2016 for occupational exposure assessment, ECHA R15:2016 [30] for consumer exposure assessment and ECHA R18:2016 [31] for environmental exposure estimations, an excel file was developed to organize important information related to the substances used and the activities performed at each stage of the life cycle. Additionally, in collaboration with polymer manufacturers, specific information on the physico-chemical characteristics of their materials have been added to collect polymers-specificity of materials released or potential transformation processes along their life cycle.

The release/emission hotspot identification was performed in a simple and pragmatic way, since this first step should be kept as easy and accessible as possible, to allow the different actors in the value chain to perform this check as a preliminary step of the exposure assessment. In our approach, a release or emission hotspot was defined by the concomitant presence of a combination of variables related to both the material or product under study, the process/activity that was performed with it and some relevant system related parameters. As reference, material intrinsic properties such as the presence of known toxic elements, the physical state (e.g., powder), the size (fine or ultrafine particles) or the shape (e.g., fiber or elongated particles) of some of the components of the material can play an important role in the release of materials. Moreover, high energy activities (e.g., spray, high energy mixing or grinding, etc.) are associated with a likely release or emission of materials. Finally, system related parameters (e.g., humidity, presence of system of containment, ventilation, engineering controls, etc.) are known to affect material emissions. For this reason, the presence and combination of the above-mentioned parameters were used to flag possible release/emission hotspots that can be further investigated using exposure assessment models or experimental testing.

As no guidelines are currently available to define whether or not a material can be released, the expert judgement and experiences acquired in previous EU projects (i.e., GUIDEnano, caLIBRAte, GRACIOUS, CIMPA, SAbyNA, ASINA, SbD4Nano,) were used to identify the hotspots of release, also in case of data gaps. The ready-to-use Excel table is reported in the online Zenodo platform. The developed Excel file was then filled in by the manufacturers to identify potential hotspots of release along the whole life cycle of the investigated epoxy-resin composite material.

The selection of appropriate experimental tests was based on information found in literature about the type of material/chemical potentially released (e.g., powder and fiber-like particles, micro-nanoplastics (MNPs)) as well as potential transformation processes occurring during the assessment scenarios [32].

For example, during the use stage conditions, [33] underlined how weathering is one of the most critical processes affecting the physical-chemical attributes of plastic materials. This is due to the physical effect of the abrasion activity through microscopic surface cracks which in turn accelerates the leaching of additives [34] and also through the thermal oxidation and photo-oxidation. These photo/thermal-oxidations trigger polymeric yellowing when exposed to near-UV and visible radiation through the generation of various free-radical reaction mechanisms, altering the surface chemistry, mainly by forming new functional groups, such as -C =O; -CO, and –OH in the presence of O/N oxides, OH radicals, and other photo-generated radicals [33]. Under weathering conditions, an increase of surface area can be detected as a result of cracking and fragmentation after exposure to Xenon light [35,36]. In addition, the geometry of the released particles also influences the release of flame retardants contained in the composite material that can be accelerated along the weathering process [37]. However, targeted analysis [38] showed the vastly different chemical profiles that could be expected from different plastic products.

Other important components in composite materials to be investigated, as part of transformation processes and their consequent transformed substances, are intentionally and non-intentionally added substances (i.e., respectively IAS and NIAS). For example, the formation of micro and nanomaterials (especially metal and metal oxide nanomaterials) can be released after the weathering of plastic material as a consequence of transformation processed of the additives contained in the plastic [39], while the behavior of IAS and NIAS in plastic debris was shown to be highly dependent on both the plastic-additive formulation and environmental factors [40].

In the work of Das et al. 2013 [41], the contribution of different reinforcing fibres in composites was investigated during accelerated weathering tests, concluding that these fibres play a dominant role in terms of performance on aged samples. In addition, the performance of a weathered composite is also influenced by the fibres structure, e.g., if the fibres are confined fibres in a reinforced polymer composite, or the number of layers. Indeed, as showed in [42], the variation in percentage of moisture during weathering tests caused an effect in the structure of tin slag polymer concrete externally reinforced with carbon fibres.

In Table 2, the likely hotspots of release are presented for each Assessment Scenarios. For example, the cutting of the carbon fibres used to produce the final composite is considered a high energy level and manual activity, with a possible release of electrostatic micro and nanofibers, which can affect workers through dermal and inhalation exposure. During mechanical recycling, grinding, sieving, cleaning of the grinder and molding activities can also be identified as potential release hotspots activities as these are high energy processes where powder of the grinded composite material, MNPs, micro and nanofibers can cause inhalation and dermal workers exposure. In the current work, only the experimental tests simulating the use stage of the composite material were reported.

For this purpose, a simulation of the exterior application of the composite material in the structural part of the train was in focus, investigating different released materials during weathering and strong abrasion activities, causing potential effects in soil and aquatic environmental compartments. Because of the presence of carbon fibres, a focus on fibre-like particles was conducted. Indeed, according to the fibre (pathogenicity) paradigm [43,44] and as stated by the World Health Organization, fibres with a length > 5 µm, a respirable diameter <3µm and an aspect ratio (A/R) > 3:1 are regarded as critical fibres as they may cause severe harm to humans upon inhalation exposure if they are sufficiently bio-durable [45]. Moreover, respirable fibres with a diameter greater than 30 nm can be classified as rigid fibres, and are considered more hazardous than non-rigid fibres [46]. Information related to the hazardous effect of the hardener used in this case study can be found in Berenguer et al. submitted.

Table 2. Hotspots of release identified and associated experimental test performed.

Life cycle stage	**Activity**	**Potential hotspot of release**	**Potential receptors of release / exposure**	**Substance of interest**	**ER/EC**	**Experimental test**
Step 1 and Step 2 – Material design (Formulation and manu-facturing) – FR resin formulation	Handling/ cutting of fibres	YES- dry solid carbon fibres, high energy level of the process, manual activity, 60’of duration	Workers	Micro and nanofibres	Inhalation, dermal	NA
Step 3 - Use	Use as exterior	YES- potential release during	Environment	Powder of the	Soil, water	Outdoor aging and

	structural part of the train	aging and abrasion		composite, micro and nano fibres, MNPs		hard abrasion
Step 4- Mechanical recycling	Grinding	YES- dry micro composite particles/powder and/or carbon fibres, high energy level of the process, manual activity	Workers	Powder of the composite, micro and nano fibres, MNPs	Inhalation, dermal	NA

ER/EC: Potential exposure route(s) / exposed environmental compartments, NA: activity excluded from the study, MNP: micronanoplastics.

2.4. Release Quantification at Identified Hotspots

2.4.1. Outdoor Aging and Hard Abrasion Test

To simulate the use stage of these materials, cascade activities (i.e., two or more tests repeated sequentially) were applied to investigate the contribution of sunlight, rain and strong abrasion once the composite would be used as an exterior part of a train.

For this reason, a climatic chamber SUNTEST XXL (ATLAS Electrical Devices) has been used to simulate outdoor UV aging conditions. Specifically, daylight filters and Xenon lamps have been used following Method A of ISO4892:2024 [47]. Up to 2000 h of accelerated aging, or nearly 3 months in the laboratory simulator, accumulated 432MJ/m2UV energy, which corresponds to roughly two years under mid-European external conditions [48]. In this study, samples were taken out of the aging device at different time slots (0-500 h – 750 h) for abrasion testing and corresponding physico-chemical characterization. The weathering was stopped at 750h of aging as the samples already showed a strong morphological alteration, e.g., possible oxidation due to the UV effect (SI1). Duplicates of each composite were prepared with a size of 10 x 10 cm for the cascade activity, while samples of 1 x 1 cm of size were prepared to analyse the total Sulphur content.

For the abrasion, a Taber Abrader with 2 wheels of 1 kg each covered with a medium abrasive paper have been used to simulate a strong and heavy abrasion (500 cycles) without using the aspiration system of the instrument. The setting of the Taber abrader and samples in the climatic chamber before starting the weathering are reported in Supplementary Information (SI1). The thickness of each sample in three different points of the abraded surface was measured before and after abrasion (after removing the powder obtained from the abrasion) using the micrometre Mitutoyo model S1012XB. Thickness measurements were presented as mean ± st.dev. of three independent measurements. An analytical balance (Denver Instrument, APX-200) has been used to weight samples and wheels with the sanding paper before and after performing abrasion. Results are reported in grams with 4 decimals for the mean and standard deviation of the two replicates of each material.

Inductively Coupled Plasma- Mass Spectrometry (ICP-MS) analysis has been conducted using the triple quadrupole ICP-QQQ (Agilent 8900) to analyse Sulphur (S) element to track the AFD hardener in each investigated sample (i.e., clean sanding paper as a blank, sanding paper after abrasion (left and right wheel paper separately) and composite samples 1 x 1 cm size before weathering). A triple quadrupole ICP-QQQ (Agilent 8900) was used after a total digestion of each investigated sample with 4 ml of concentrated ultrapure nitric acid (HNO_3 70%) and 1 mL of concentrated ultrapure hydrochloric acid (HCl 37%) in an analytical microwave at 280 °C and each weighted sample before the digestion. The digestion residue obtained is then diluted appropriately to analyse Sulphur (S). Quantification of this element is performed by interpolation on a calibration line prepared from commercial standards of the elements of interest. The test is performed in duplicate and results expressed as mean ± st.dev. of the independent measurements.

Scanning Electron Microscopy (SEM) analysis has been conducted to study the powder generated during the abrasion collected with few drops of milliQ water and deposited on SEM stubs to determine particle morphology and size distribution of the material released. SEM analysis using JEOL J-7100FE, operating at 20 keV with a secondary electron detector was used and prior to the SEM observation, the specimens were coated with carbon to increase their conductivity. To make size measurements on SEM images, manual measurement of particle size was performed using ImageJ software. Spheroidal and fibre particles were counted and measured separately to obtain information on size for spheroidal particles and on number, diameter, length and A/R for fibre particles. At least 100 particles measurements were performed and results are reported as mean ± st.dev. of the diameter in μm and percentage of fibres-like particles present in each sample.

2.4.2. Micro- and Nanoplastic Spot-Check

In the microplastic spot-check analysis, the NanoRelease sampling protocol was applied before and after 2000 h of UV aging of the test specimen. The purpose of the NanoRelease protocol is to remove loosely attached secondary micro- and nanoplastics from the surface of the (aged) test specimen and to disperse them in water for subsequent analysis [49]. The pristine and aged specimen all had the same surface dimensions of 6 cm2. For sampling, 6 mL of ultrapure water were filled in a glass container, and one specimen was placed onto it (with the aged side facing the water). In the next step, the sample was treated in the ultrasonic bath at 100% power for 1 hour. During this time, regular cooling with ice was necessary to maintain the temperature below 40 °C. After the ultrasonication treatment, the plate was removed, and the liquid was collected using a syringe. The collected volumes, the initial volume used for the treatment, and the sizes of the specimen were documented. Blank measurements in absence of a specimen were conducted to determine the particle background. Three different techniques were used for subsequent analysis of released micro- and nanoplastics, as well as dissolved organic carbon (DOC): a particle counter, an analytical ultracentrifugation (AUC) and part of the solution was filtered < 0.02 μm to assess the release of water-soluble non-particulate organics (DOC) via TOC measurements.

A particle counter was used to quantify the released fragments from 1- 120 μm: measurements were done with an Abakus® Mobil Fluid laser particle counter (Klotz GmbH) equipped with a laser sensor LDS 2148(0) (1-120 μm). For this purpose, 0.7 mL of the NanoRelease dispersion was filled up to 500 mL with ultrapure water. For sensor protection the sample was filtered with a 190 μm pre-filter (nylon, Rotert). The measurement was performed with 200 mL of the sample. Data evaluation was performed with C.A.R. Lab. Duplicate samples were measured and values for blank measurements were subtracted.

AUC was used to quantify the mass of released nanoplastics from 20-999 nm: The AUC-Beckman XL centrifuge is equipped with an interference optical system synchronized to the centrifugal rotation, so that the colloidal sedimentation profile during centrifugation is monitored over time. By adjusting the centrifugation speed, the mass concentration and particle size distribution were determined in three overlapping size intervals of 10-150 nm (12 000 rpm ≙ 10 500 rcf), 40-800 nm (3 000 rpm ≙ 650 rcf) and 300-5000 nm (1 000 rpm ≙ 70 rcf); with 3 hours centrifugation time each. For data evaluation of the absorption profiles (resolved in time and radius) SedFit v14.0 was used with the corresponding polymer density. Duplicate samples were measured and values for blank measurements were subtracted.

Part of the solution was filtered < 0.02 μm to assess the release of water-soluble non-particulate organics (DOC) via TOC measurements: the filtered NanoRelease sample was diluted with ultrapure water with dilution factors of 1:10 and 1:20 and total carbon (sample combusted catalytically on a Pt/Al_2O_3 catalyst in an oxygen stream at ca. 680 °C) and total inorganic carbon (sample acidified with 25 wt.-% phosphoric acid) were quantified as CO2 via NDIR detection (Shimadzu TOC-L). DOC was

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calculated as the difference between total carbon and total inorganic carbon. Duplicate samples were measured.

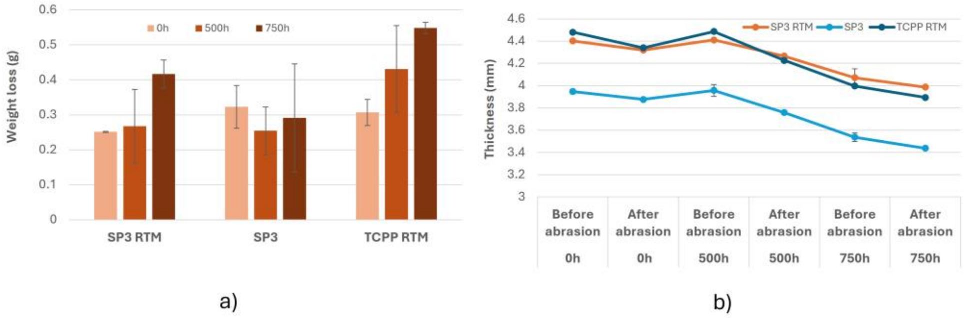
3. Results and Discussion

3.1. Release Quantification at Identified Hotspots

3.1.1. Outdoor Aging and Hard Abrasion

The effect related to the sequential release experiments of hard abrasion and outdoor aging is presented in terms of weight loss of the sample, thickness and elemental analysis of the powder released during abrasion.

For the weight loss (Figure 2, a), it is possible to notice differences between the effect of the abrasion alone (represented as the weight loss at 0h) and the effect of the combination of abrasion and weathering (i.e., at 500h and 750h). Higher variability of the weight loss after the weathering of SP3 RTM, SP3 and TCPP RTM between the two repetitions was observed compared to the variability of the samples before weathering, probably due to the effects of water and light on samples that that probably compromise the sample surface, creating a not homogeneous surface with weaker points that release more materials when subjected to the hard abrasion. In addition, no significant differences can be noticed between the SSbD1 composite (i.e., SP3 RTM) and its corresponding version without carbon fibres (i.e., SP3). Higher release of material after weathering and abrasion of the benchmark material (i.e., TCPP RTM) can be observed compared to the SSbD alternative (i.e., SP3 RTM). A reduction of the thickness of each material can be observed after the abrasion both in weathered and not weathered samples (Figure 2, b). Lower values can be detected for samples without carbon fibres (i.e., SP3) compared to the ones containing carbon fibres (i.e., SP3 RTM, TCPP RTM) and a progressive decrease of the thickness along the aging for all the samples. Moreover, after aging, a slight thickness increase was detected, probably due to the effect of the water and the light during the 500 hours aging that could alter the structure of each sample.



a) b)

Figure 2. Weight loss (in %) of each sample after abrasion at 0h, at 500h and 750 hours of aging (a) and thickness measurements (mm) of aged and not aged samples before and after the abrasion (b).

Considering the release investigations by elemental analysis expressed as wt. % (Table 3), sulphur – element used to track AFD release - is released in higher quantities from the samples with no carbon fibres (i.e., SP3) compared to the one containing the fibre material (i.e., SP3 RTM, TCPP RTM) during the hard abrasion test. This is because the carbon fibres functionality improves the stability and the resistance of the composite samples. Similar sulphur concentrations are obtained following the abrasion of SP3 RTM6 and TCPP RTM1.1 which does not permit to discriminate the release of AFD between the SSRbD alternative (halogen-free FR) and the benchmark composite (halogenated FR) during the simulation of the use stage. Similar releases between weathered and not weathered samples can be detected showing that the weathering does not influence the AFD release during the use stage of the various materials.

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Table 3. S content (%w/w) after total digestion of 1x1 cm2 sample and corresponding total S concentration calculated for abraded volume sample.

Sample	S (% w/w) – 1x1 cm^2 sample (Mean ± SD)	S (% w/w) related to the total abraded sample volume (Mean ± SD)
SP3RTM	1.73 ± 0.06	51.92 ± 1.77
SP3	6.30 ± 0.11	188.92 ± 3.22
TCPP RTM	1.53 ±0.01	46.05 ± 0.26

According to SEM observations (Figure 3, 4), the particles collected after the abrasion of non-aged and aged materials have a quite broad size distribution, characterized by particles having irregular spheroidal shapes. In samples containing the carbon fibres materials (SP3RTM and TCPP RTM), fibre fragments have different lengths.

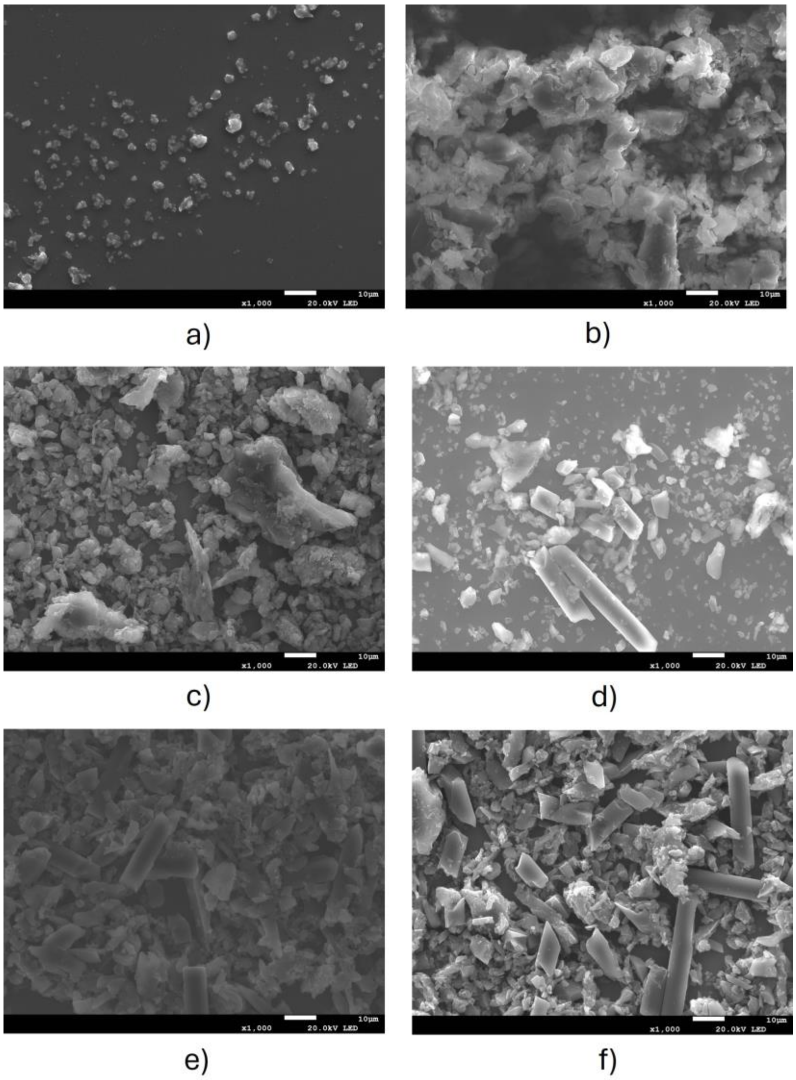


Figure 3. SEM images of powder released after abrasion of a) SP3 at 0h, b) SP3 at 500h and c) SP3 at 750h, d) SP3 RTM at 0h, e) SP3RTM at 500h and f) SP3 RTM at 750h.

After weathering, particles seem to be more aggregated, and the determination of the particles size is more challenging due to the presence of overlapping particles with very similar contrast in the

SEM images. This increased aggregation makes it more difficult to measure small size particles and results in an apparent larger particle size.

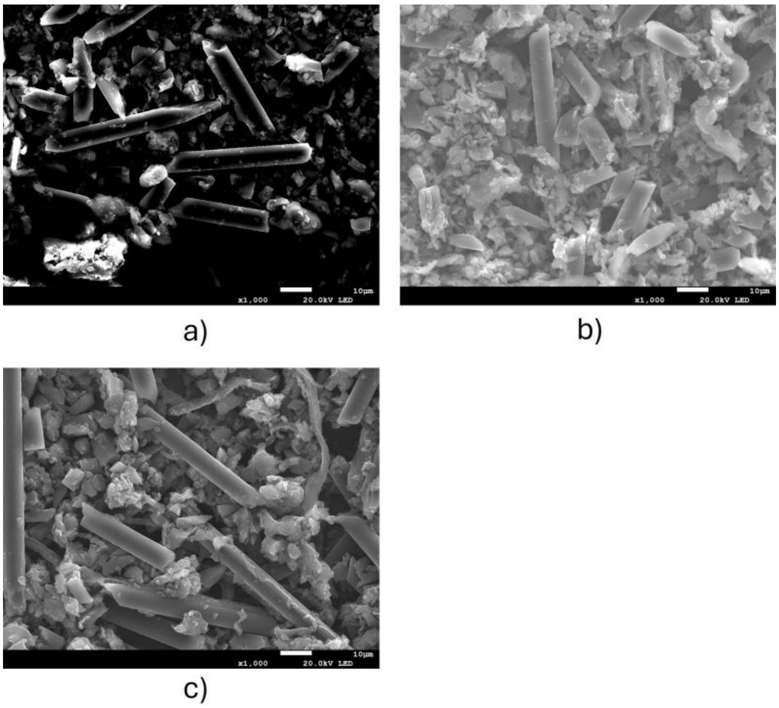


Figure 4. SEM images of powder released after abrasion of TCPP at a) 0h, b) at 500h, and c) at 750h.

Regarding the fibres released from the composites containing the carbon fibres materials (RTM), in all observed samples, the fibre diameter was 6.5 ± 0.5 µm, therefore they can be considered as rigid fibres. The fibres diameter did not change after the first abrasion and the subsequent weathering plus abrasion, indicating that these types of fibres are not affected by these processes. Regarding the length of fibres, very few of them were shorter than 5µm after the first abrasion, and their length remained quite constant after the subsequent weathering plus abrasion. Accordingly, the fibres A/R remained higher than 3:1. The number of fibres per picture and the number of fibres with A/R>3, for aged and not aged samples, were quite similar, suggesting that the SSbD alternative (i.e., SP3 RTM) have the same behavior when subjected to the combined weathering and abrasion. In Table 4, the measurements for length, diameter and the percentage of fibres with an A/R higher than 3 are reported for 15 fibres of each sample, where the highest value was obtained for the TCPP material abraded and aged for 750h.

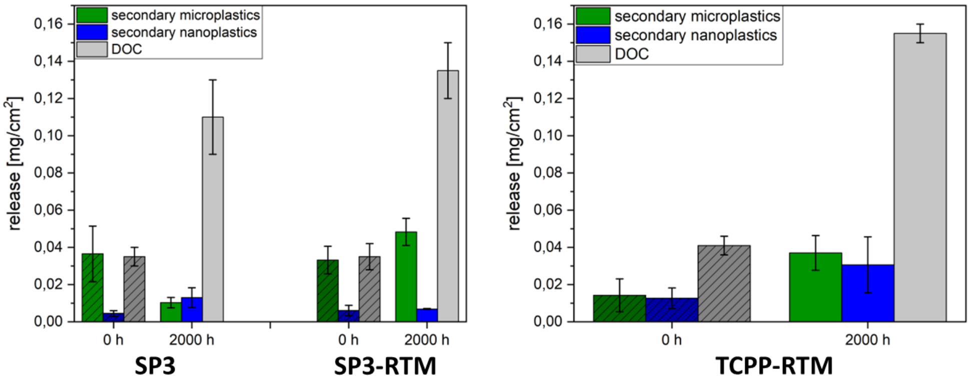
Table 4. Number of fibres detected in SEM images and percentage of elongated particles with Aspect/Ratio (A/R) higher than 3 for the samples containing carbon fibres.

Sample	Weathering	Diameter (µm)	% elongated particles with A/R>3
TCPP RTM	0h	5.92±0.88	53%
	500h	6.75±0.52	60%
	750h	6.99±0.72	73%
SP3 RTM	0h	6.64±0.49	60%
	500h	6.77±0.32	53%
	750h	6.77±0.55	67%

3.1.2. Outdoor Aging and Micro- and Nanoplastic Quantification

Each species of SP3 with and without carbon fibres (SP3 RTM and SP3 respectively) and the TCPP Reference with carbon fibres (TCPP RTM) was measured in duplicate. The measured raw data obtained with the three different analytical techniques was used to calculate the release of each species in mass per (aged) surface area. Figure 5a shows the comparison of releases from the SP3 (without carbon fibres) and the SP3-RTM (with carbon fibres) material, each pristine and aged. Figure 7b shows the releases from the TCPP-RTM Reference pristine and aged. After UV aging, the DOC release is increased 3-4-fold in SP3 as well as in SP3-RTM. In the case of SP3, the microplastic release is decreased after UV aging, and the nanoplastic release only slightly increased. In contrast to that, an increase in micro- and nanoparticle release from the SP3-RTM composite material was detected after UV aging. In this context, it must be noted that micro- and nanoparticles released from the composite materials are most likely composite fragments as well. However, due to the definition of microplastics, they all must be classified as microplastics, if their polymer content is at least 1%, which is very likely the case, but can currently not be proven with the available analytical techniques. In the case of the TCPP-RTM Reference without carbon fibres, an increase of micro-, nanoplastic and DOC release was detected after UV aging (Figure 5b). Particle releases from pristine TCPP-RTM Reference samples were lower compared to pristine SP3 samples (with and without carbon fibres). The nanoparticle release from the TCPP-RTM Reference detected after 2000h UV aging is however higher than the nanoparticle release from SP3 and SP3-RTM after the same aging duration. Compared to the pristine TCPP-RTM, the micro- and especially the nanoparticle release increased after aging.

Comparing the Reference material (i.e., TCPP-RTM) and the SSRbD alternative material (i.e., SP3-RTM), the microparticle release from the Reference was in most cases lower than from the SSRbD product, but the nanoparticle release was, especially after aging, higher than the nanoparticle release from any other SSbD material (pristine and aged).



a) b)

Figure 5. Release of secondary microplastics, nanoplastics and DOC in mg/cm² from the reference (b) and the SSbD alternative (a) before and after UV aging.

Overall, the comparative analysis between the SSbD alternative (SP3 RTM) and the benchmark material (TCPP RTM) revealed distinct differences in release behavior under simulated use and aging conditions. The SSbD composite consistently demonstrated reduced material release during both weathering and abrasion scenarios compared to the benchmark containing halogenated flame retardant, suggesting enhanced durability and resistance to environmental stressors. Notably, the release of MNPs from the SSbD composite was generally lower or comparable to the benchmark, particularly in the nanoparticle fraction after aging, which is critical, given the heightened concern over nanoparticle emissions.

The obtained results therefore underscore the effectiveness of the SSbD approach in achieving its core objectives: minimizing hazardous releases, enhancing material recyclability, and supporting safer product innovation. By integrating non-halogenated flame retardants and reversible hardening technologies, the SSbD composite not only meets functional performance requirements for railway applications but also addresses key sustainability and safety criteria. The systematic identification and quantification of release hotspots throughout the product life cycle demonstrate how SSbD methodologies can proactively guide material selection and process optimization. The observed reduction in material release, especially under stress conditions that mimic real-world use, aligns with the SSbD framework's emphasis on source reduction of emissions and supports regulatory trends such as the EU's restrictions on microplastics and the upcoming Ecodesign for Sustainable Products Regulation. Importantly, the findings highlight the value of early-stage release assessment in the innovation process, enabling the anticipation and mitigation of potential risks before large-scale deployment.

For workers, the identification of release hotspots during manufacturing and end-of-life stages (e.g., fiber handling, grinding) provides insights for exposure mitigation, including technical measures and personal safety equipment. The SSbD composite's lower propensity for releasing hazardous fibers and particles during high-energy processes directly translates to reduced inhalation and dermal exposure risks. From an environmental perspective, the decreased release of MNPs, as well as other substances of concern, supports ecosystem protection and aligns with circular economy principles by ensuring that recycling and reuse must not inadvertently increase pollution.

5. Conclusions

This study presents a preparatory work for the development of a more structured methodology for assessing material release within the SSbD framework, specifically applied to an epoxy-resin composite intended for railway applications. By integrating expert knowledge, regulatory guidance, and experimental validation, the approach enables early identification of release hotspots across the product life cycle – from manufacturing to end-of-life. The developed Excel-based template for release hotspot identification, grounded in ECHA guidelines, facilitated a systematic screening of potential release scenarios. Experimental simulations of identified hotspots at the use stage allowed quantification of particles, fibres, and MNPs emissions. Comparative analysis between the benchmark and the SSRbD alternative demonstrated that the newly developed recyclable composites can also reduce material release, especially under weathering and abrasion conditions.

The findings underscore the importance of incorporating release assessments early in material innovation to guide safer and more sustainable design choices, especially to investigate releases of Substances of Very High Concern (SVHC) and their transformation processes along the life cycle of a product. Moreover, the results provide a foundation for developing a scoring system that integrates release data with hazard profiles, enabling a more holistic SSbD evaluation.

Future work will focus on refining the scoring methodology, validating the approach across broader material types, and exploring its integration into regulatory and industrial decision-making processes. Ultimately, the developed methodology provides a transparent, reproducible methodology to inform regulatory alignment, safer substitution, and data-driven material selection, contributing to the advancement of SSbD practices by offering a pragmatic tool for anticipating and mitigating environmental and human exposure risks associated with plastic-based materials.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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Abbreviations

The following abbreviations are used in this manuscript:

AUC	Analytical ultracentrifugation
DOC	Dissolved Organic Carbon
EC	European Commission
ECHA	European Chemicals Agency
FR	Flame retardants
IAS	Intentionally added substances
ICP-MS	Inductively Coupled Plasma- Mass Spectrometry
JRC	Joint Research Centre
MNPs	Micro- and nanoplastics
NIAS	Non-intentionally added substances
SEM	Scanning Electron Microscopy
SSbD	Safe and Sustainable by Design
SVHC	Substances of Very High Concern
TCPP	Tris(1-chloro-2-propyl) phosphate

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