sustainability

MDPI

Article

Early-Stage Simplified SSbD Screening of a Removable, PVC-Free Screen-Printing Ink: A Qualitative Life Cycle Perspective

Olga Lysenko [1,*], Sahar Safarian [2,*], Pavinee Hasselberg [2], Nilay Elginoz [1], Tomas Rydberg [2], Maja Halling [1], Steffen Schellenberger [3], Jutta Hildenbrand [2], Gustav Utas [4], Yiming Jia [4,5] and Romain Bordes [5]

1 IVL Swedish Environmental Research Institute, 11428 Stockholm, Sweden; nilay.elginoz.kanat@ivl.se (N.E.); maja.halling@ivl.se (M.H.)
2 IVL Swedish Environmental Research Institute, 41133 Gothenburg, Sweden; pavinee.hasselberg@ivl.se (P.H.); tomas.rydberg@ivl.se (T.R.); jutta.hildenbrand@ivl.se (J.H.)
3 RISE Research Institutes of Sweden, Environment and Sustainable Chemistry Unit, 11428 Stockholm, Sweden; steffen.schellenberger@ri.se
4 Vividye AB, 41133 Gothenburg, Sweden; gustav@vividye.com (G.U.); yimingj@chalmers.se (Y.J.)
5 Department of Chemistry and Chemical Engineering, Chalmers University of Technology, 41258 Gothenburg, Sweden; bordes@chalmers.se
* Correspondence: olga.lysenko@ivl.se (O.L.); sahar.safarianbana@ivl.se (S.S.)

Abstract

This paper presents a qualitative sustainability assessment of an innovative, water-based, partially bio-based, and potentially removable screen-printing ink designed to replace conventional PVC-based inks in the textile industry. The assessment is conducted in alignment with the European Commission's tiered Safe and Sustainable by Design (SSbD) framework, applying a simplified screening approach suitable for innovations with limited sustainability data availability. The evaluation is conducted using the LCBROM (Life Cycle Based Risk and Opportunity Mapping) methodology, which is a structured approach designed to identify potential environmental, economic, and social drawbacks and benefits throughout the product's life cycle, from production and use to end of life. The screening incorporates the MET+Ec+S matrix (Material, Energy, Toxicity, and Economic and Social dimensions), providing a comprehensive overview of the sustainability performance of the removable PVC-free ink at each stage of its life cycle. The novel removable PVC-free ink formulation incorporates bio-based pigments, thickeners, and plasticisers, and is designed to facilitate recyclability and reuse in textile applications. Compared to traditional plastisol inks, the screening indicates potential reductions in toxicity and environmental persistence compared to PVC-based plastisol inks, subject to validation in future quantitative studies. However, key trade-offs include reliance on fossil-based ingredients (as bio-based alternatives are still being developed), increased material costs, and durability concerns. Despite these issues, the removable PVC-free ink's compatibility with existing printing infrastructure and alignment with emerging EU sustainability regulations indicate its potential relevance for circular textile production, subject to validation through quantitative life-cycle assessment and pilot-scale implementation. The results do not constitute a quantitative life cycle assessment but instead provide a structured qualitative basis for guiding further development, data collection, and future LCA modeling. By explicitly positioning the work within a simplified SSbD tier, this study demonstrates how early-stage screening can support innovation design while transparently addressing uncertainty and trade-offs.

Check for updates

Academic Editor: Giovanni De Feo

Received: 26 January 2026
Revised: 25 February 2026
Accepted: 17 March 2026
Published: 19 March 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Keywords: sustainable screen printing; removable PVC-free ink; LCBROM; qualitative life cycle assessment; circular textiles; Safe and Sustainable by Design (SSbD)

1. Introduction

1.1. Background and Technological Context: PVC-Based Screen-Printing Inks and Circularity Constraints

Textile printing represents a technically sophisticated and environmentally intensive stage in garment manufacturing. Among available technologies, screen printing remains one of the most widely applied methods due to its scalability, high pigment loading capacity, reproducibility, and compatibility with diverse textile substrates, including cotton, polyester, polyamide, and blended fabrics. Its dominance in mass production is strongly linked to the widespread use of plastisol inks [1].

Plastisol inks are dispersions of polyvinyl chloride (PVC) particles in high-boiling plasticizers [2,3]. During curing (typically 140–180 °C), plasticizer absorption induces particle swelling and subsequent fusion into a continuous thermoplastic film [4,5]. This film-forming mechanism enables high pigment loading, opacity, abrasion resistance, wash durability, and strong adhesion to fibrous substrates [6,7]. However, the chlorine-based polymer backbone, the high plasticizer content, and the potential for additive migration are associated with significant environmental and health concerns throughout the life cycle [8–10].

PVC production is chlorine-based and energy-intensive, involving vinyl chloride monomer (VCM), which is classified as a Group 1 human carcinogen by the International Agency for Research on Cancer [11]. Industrial production routes and life-cycle inventories indicate substantial energy demand and emissions associated with chlor-alkali processes and VCM synthesis [12,13]. Across its life cycle, PVC has been associated with persistent organic pollutants, hazardous additives, and end-of-life management challenges, including additive leaching and limited recyclability [8,9,14,15]. To achieve flexibility, PVC formulations typically contain high plasticizer contents, commonly in the range of 30–60 wt.% [5,16]. Historically, phthalates such as DEHP and DBP have been widely used, and several are listed as Substances of Very High Concern (SVHC) under the European Chemicals Agency regulatory framework [17]. Even when alternative plasticizers are employed, concerns remain regarding additive migration, potential endocrine disruption, and long-term environmental persistence [18,19].

Beyond chemical hazards, plastisol inks introduce structural barriers to textile circularity. The fused PVC layer forms a strongly adherent polymer film with high interfacial bonding to fibrous substrates [2,6,15], making mechanical separation without fiber damage technically challenging. In mechanical recycling systems, residual coatings and prints act as contaminants, reducing fiber quality and limiting the potential for closed-loop recycling [20,21]. In chemical recycling processes, heterogeneous polymer layers and additive mixtures interfere with depolymerization reactions and solvent-based purification pathways [22–24]. Moreover, polymer-based textile coatings contribute to microplastic release during laundering and abrasion. Experimental studies have demonstrated that synthetic textiles fragment under mechanical stress, releasing microfibers into wastewater streams [25–27]. These particles are not completely removed during wastewater treatment and accumulate in aquatic environments [28,29].

As the textile sector transitions toward circular economy models, material-level incompatibilities have emerged as systemic bottlenecks [30,31]. Life-cycle analyses demonstrate that coatings and prints—despite their low mass fraction—significantly impair fiber recov-

ery and recycling efficiency [25,26]. In both mechanical and chemical recycling systems, polymer-based surface treatments reduce recyclate quality and process efficiency [15]. Regulatory and policy drivers further intensify reformulation pressure. The European Commission's Chemicals Strategy for Sustainability and the Ecodesign for Sustainable Products Regulation (ESPR) embedded Safe-and-Sustainable-by-Design principles into future textile regulation [32,33]. These frameworks require materials to demonstrate reduced hazard profiles, improved circular compatibility, and minimized life-cycle impacts.

However, viable replacements for PVC-based plastisol inks face substantial materials engineering constraints. Screen-printing inks must simultaneously satisfy rheological stability for mesh transfer, controlled curing behavior, strong adhesion to hydrophilic and hydrophobic fibers, high pigment dispersion stability, mechanical flexibility under repeated deformation, wash and abrasion resistance, and color fidelity and opacity.

Replacing PVC alters the fundamental polymer matrix properties, including glass transition temperature (Tg), film formation behavior, interfacial adhesion mechanisms, and durability. Water-based systems, bio-based binders, and hybrid dispersions offer potential pathways but introduce trade-offs in drying energy demand, durability, or cost [34]. Therefore, innovation in this domain requires balancing performance chemistry with sustainability objectives [35,36].

The present study investigates a novel, water-based, partially bio-based, PVC-free screen-printing ink designed with an additional functional attribute: removability. Unlike conventional plastisol systems that form irreversible thermoplastic films, the new formulation is engineered to allow detachment from the textile substrate under controlled conditions without fiber degradation. This design aims to enhance compatibility with both mechanical and chemical recycling pathways, thereby reducing contamination in circular textile flows.

Such a functionality directly links polymer chemistry, adhesion science, and circularity performance—underscoring the necessity of evaluating not only toxicity reduction but system-level sustainability implications.

Given the regulatory pressure to phase out hazardous PVC-based formulations and the structural recycling barriers associated with plastisol inks, evaluating alternative formulations at early development stages is scientifically important to avoid unsustainable technological lock-in.

1.2. Necessity of Early-Stage Sustainability Screening Prior to Upscaling, LCA, and SSbD Implementation

Emerging materials are typically developed at low technology readiness levels (TRLs), where process parameters and supply chains remain uncertain [37]. While Life Cycle Assessment (LCA), standardized under ISO 14040 and ISO 14044 [38,39], enables us to quantify the environmental impacts, both direct and indirect, of a product [40,41], its application to early-stage technologies faces methodological challenges due to incomplete inventory data and scaling assumptions [42,43]. Detailed LCAs under such conditions may generate results with false precision, as parameter uncertainty and background database proxies can dominate outcome variability [44,45]. Consequently, sustainability science increasingly recommends ex-ante or screening-level assessments to guide early formulation decisions [46,47]. In accordance with the European Commission's tiered SSbD framework [48], early-stage innovations with limited quantitative data should undergo screening-level assessment prior to full life-cycle modeling. Therefore, this study applies a simplified SSbD screening approach to identify potential risks and opportunities at low sustainability maturity, rather than to quantify environmental impacts.

Screening-level assessments serve multiple critical purposes:

(1) Prevention of unsustainable technological lock-in

Once pilot-scale infrastructure or supply chains are established, reformulation becomes economically and technically constrained [49,50]. Early screening allows identification of high-risk substances, energy-intensive steps, or social concerns before irreversible investments occur.

(2) Identification of environmental hotspots at the formulation level

In ink systems, small compositional differences (e.g., binder type, crosslinker chemistry, plasticizer fraction) can significantly affect toxicity, recyclability, and end-of-life behavior [51]. Early screening supports informed substitution before scale-up.

(3) Strategic guidance for data generation prior to full LCA

Qualitative or semi-quantitative screening can identify which parameters (e.g., curing energy, solvent recovery efficiency, additive migration rates) require prioritized measurement in subsequent quantitative studies [43,52].

(4) Integration with Safe-and-Sustainable-by-Design (SSbD)

The SSbD framework promoted by the European Commission represents a forward-looking strategy to ensure that materials and chemicals are inherently safe, sustainable, and circular. However, the successful implementation of SSbD critically depends on early identification of potential environmental, social, and economic risks in the material design phase [53,54]. Emerging materials, particularly at low TRLs, are characterized by high uncertainty regarding composition, process conditions, energy demand, and end-of-life behavior. Attempting to apply SSbD without preliminary sustainability insights risks overlooking critical hotspots, embedding non-optimal design choices, or generating false precision in later-stage assessments [45,48].

Early-stage qualitative or semi-quantitative sustainability screening provides a structured approach to prioritize environmental and social concerns, identify high-risk substances, and guide experimental design before extensive SSbD evaluation is conducted (Figure 1). By mapping potential toxicity, resource intensity, recyclability, and social implications at the formulation level, these screening methods allow researchers and designers to focus SSbD efforts on the most impactful interventions, avoiding costly reformulations at pilot or industrial scales. Screening also facilitates the iterative nature of SSbD by enabling rapid feedback loops: design choices can be adjusted in response to early sustainability insights, which supports a more informed, evidence-based development pathway.

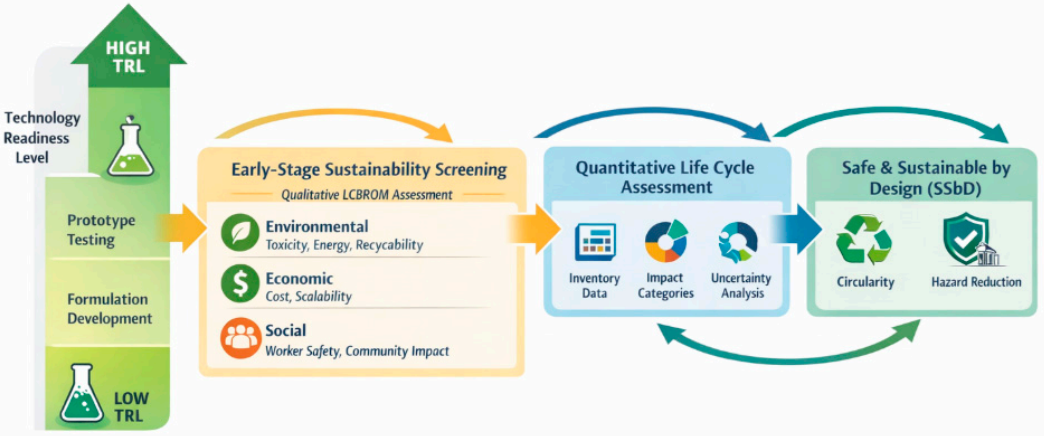


Figure 1. Integration of early-stage sustainability screening in materials innovation and circularity. Source: The figure generated by the author's own work.

In the context of circular textile systems, removability introduces complex trade-offs. Enabling fiber recovery may influence adhesion strength, durability, or use-phase performance. These trade-offs cannot be understood solely through performance testing or hazard classification; they require system-level evaluation across production, use, and end-of-life stages.

Given the low TRL and limited sustainability data maturity, including the absence of industrial-scale inventory data for the investigated formulation, this study applies a structured, qualitative life-cycle-based screening approach using LCBROM. Rather than replacing quantitative LCA, this method functions as a pre-assessment stage. Empirical inputs include the following:

- Developer-provided formulation and process data
- Two structured LCBROM questionnaire rounds
- Stakeholder workshops
- Structured evaluation across environmental (MET), economic (Ec), and social (S) dimensions

This approach enables the identification of potential sustainability benefits (e.g., improved recyclability, reduced PVC-related hazards) and risks (e.g., performance trade-offs, energy demand shifts, cost implications), while transparently documenting the sources of uncertainty. By systematically linking material composition, functional performance characteristics, and life-cycle considerations, the study provides an evidence-based foundation for the following:

- Subsequent quantitative LCA
- Targeted data collection
- Regulatory alignment under SSbD
- Technology optimization prior to scale-up

Thus, early-stage sustainability screening is not a substitute for quantitative assessment but a scientifically necessary precursor to responsible materials innovation.

2. LCBROM Methodology

2.1. Positioning Within the SSbD Tiered Framework

Although the technical readiness level (TRL) of the removable PVC-free ink formulation is mid-range, the sustainability data maturity is low: industrial-scale production data, detailed life cycle inventories, and validated end-of-life performance metrics are not yet available. In accordance with SSbD methodological guidance, this study therefore applies a simplified screening assessment characterized by the following:

- Qualitative evaluation of key safety and sustainability dimensions.
- Narrow system boundaries (production, use, and end-of-life stages).
- High uncertainty of data and results.
- Identification of potential risks and opportunities rather than quantified impacts.

The objective is not to demonstrate environmental superiority but to prioritize sustainability hotspots and guide further data generation and design refinement.

The LCBROM framework [55]—Life-Cycle-Based Risk and Opportunity Mapping—is employed in this work for simplified screening assessment to recognize important economic, social, and environmental hazards associated with early-stage innovations across different proceedings.

2.2. LCBROM Screening Procedure

The LCBROM framework [55] adopts an iterative process, as illustrated in Figure 2, that emphasizes ongoing stakeholder involvement to identify potential risks and opportunities associated with these technological developments.

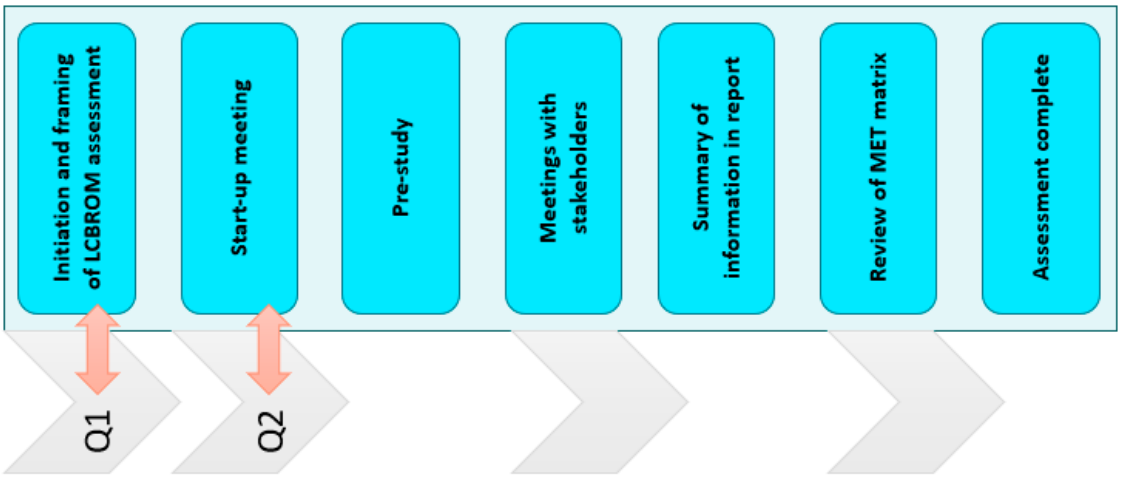


Figure 2. The stages of the applied methodology. Source: Reproduced from [55,56] with permission.

Stakeholder mapping was conducted to ensure representation across the textile value chain. An initial questionnaire (Q1) was distributed to clarify the problem definition, identify benchmark technologies, and map relevant life cycle stages. A kick-off workshop was subsequently conducted to refine system boundaries, discuss preliminary responses, and co-develop a life-cycle flowchart for the innovation.

A second questionnaire (Q2) was then distributed to collect more detailed qualitative information on material composition, energy demand, toxicity aspects, and perceived economic and social implications.

In parallel, a targeted literature review was conducted to contextualize stakeholder input within existing life cycle assessments, risk assessments, and sustainability studies relevant to textile printing technologies.

The collected information was synthesized using the expanded MET+Ec+S matrix (Material, Energy, Toxicity + Economic and Social dimensions) (Table 1), which structures identified risks, opportunities, and uncertainties across production, use, and end-of-life stages. The matrix constitutes the primary analytical output of the screening.

Table 1. MET+Ec+S matrix used in LCBROM.

Life Cycle Stage	Materials	Energy	Toxicity	Economic	Social
Production	Any non-renewable resources, such as scarce metals? Emissions from material production?	Energy for activation and product production, and transportation?	Are some of the ingredients toxic in production? How closed is the process? Is there a risk of leakage?	Will the new material or process increase/save production costs? If so, how? How will the materials affect the supply chain dynamics and market competitiveness?	Are there any occupational health and safety risks for workers that will arise with new materials? Are there any positive impacts (opportunities) related to the new materials (e.g., technology development, local employment, decreased health and safety risks)?

Table 1. *Cont.*

Life Cycle Stage	Materials	Energy	Toxicity	Economic	Social
Use	Any process chemicals, cleaning?	Electricity for operation (How much or energy-intensive process?)	Any release of toxic chemicals during use or maintenance of the product?	Are there any potential economic benefits for end-users, such as lower maintenance or operational costs? Could the new material or process enable new market opportunities or applications?	Can the use of new materials have a negative or positive impact on consumers' and/or children's health and safety?
Disposal	Recycling potential?	Incineration? Landfill? Recycling? Energy use or potential energy recovery?	Landfill? Toxic emissions from incineration?	Will the disposal of the new materials require additional costs (e.g., new recycling infrastructure)? Could the use of the new material reduce long-term costs for waste management, such as lower emissions or improved recyclability?	Will the new materials pose risks to workers during waste handling? Any opportunity during risk handling?

As LCBROM is iterative, follow-up discussions were conducted to validate interpretations and refine matrix classifications.

2.3. Data Basis and Analytical Treatment

The assessment is based exclusively on qualitative and semi-structured data sources appropriate for early-stage innovation screening. Primary inputs included the following:

- Developer-provided technical descriptions of material categories, production steps, laboratory-scale batch size (0.5 kg), and qualitative energy demand.
- Structured responses to two LCBROM questionnaires (Q1 and Q2).
- Stakeholder workshop discussions.
- Targeted peer-reviewed literature on PVC-based plastisol inks, water-based alternatives, and textile recycling constraints.

Due to intellectual property protection and the early development stage of the formulation, exact chemical identities, quantitative composition data, and detailed life-cycle inventory datasets were not available. No direct environmental measurements (e.g., emission testing, energy metering, toxicity assays) were conducted within this study.

All matrix entries were derived through a qualitative synthesis of stakeholder inputs and the literature. Where statements relied on developer expectations rather than empirical validation, this was explicitly reflected in the matrix as uncertainty.

The screening does not replace quantitative life cycle assessment (LCA). However, it provides a structured approach to prioritizing potential sustainability hotspots for future investigations.

Stakeholders represented the following: technology developers (n = 1), textile manufacturing and finishing companies (n = 2), a retail company operating in the Scandinavian market (n = 1), and sustainability assessment practitioners from research institutes (multiple participants).

The technology developers provided qualitative technical data, including material categories, functional roles of formulation components, laboratory-scale production steps, batch size (0.5 kg), sourcing region (EU-based suppliers), and general statements regarding energy demand relative to conventional paint production. Developers also described

the intended removability mechanism and compatibility with existing screen-printing equipment. Textile industry representatives provided operational insights regarding printing compatibility, durability requirements, drying energy considerations, and potential cost implications. Retail representatives contributed perspectives on consumer quality expectations, price sensitivity, and practical considerations related to sorting and end-of-life handling. These contributions informed the economic and social dimensions of the screening rather than providing quantitative environmental performance data.

All data from questionnaire responses, workshop discussions, and developer-provided information were synthesized into the MET+Ec+S matrix.

Each identified issue was classified according to predefined criteria:

Opportunity (green): credible qualitative evidence suggested potential sustainability improvement relative to the benchmark system.

Risk (red): trade-offs, negative impacts, or systemic barriers were identified.

Uncertainty (yellow): insufficient data prevented robust classification.

Classifications were determined through iterative discussion during workshops and cross-referencing with peer-reviewed literature. Disagreements or high uncertainty were explicitly recorded and reflected in the matrix entries.

Given the early stage of development and limited quantitative data availability, uncertainty was treated as an explicit analytical dimension rather than as a limitation to be minimized. Uncertainty was addressed through three mechanisms:

- Explicit flagging within the matrix: Issues lacking sufficient empirical basis were classified as "uncertainty" (yellow) rather than forced into opportunity or risk categories.
- Triangulation of sources: Questionnaire responses, workshop discussions, developer-provided information, and peer-reviewed literature were cross-referenced to reduce reliance on single-source claims.
- Separation of assumption from evidence: Developer expectations and stakeholder perceptions were clearly distinguished from validated environmental performance data.

This explicit management of uncertainty ensures that the MET+Ec+S matrix reflects both identified sustainability opportunities and knowledge gaps inherent to early-stage innovation assessment.

3. Results

3.1. Problem Definition: Insights from LCBROM and Literature

As part of the LCBROM pre-study, a targeted literature review was conducted to characterize the benchmark system, PVC-based plastisol inks, and to identify sustainability-relevant hotspot domains prior to matrix evaluation.

3.1.1. Environmental Impact

Despite its advantages, traditional screen-printing practices raise several environmental concerns, primarily related to the chemical composition of conventional inks. Plastisol inks, commonly used in industry, contain polyvinyl chloride (PVC) as the main film-forming component and often rely on volatile organic compounds (VOCs) as solvents. These VOCs can evaporate during the curing process, contributing to air pollution and occupational health risks.

In response, recent advancements have introduced more sustainable alternatives, often accompanied by a shift towards water-based systems. These include biodegradable binders, green solvents, and water-based ink systems, which collectively reduce the environmental impact of chemical emissions and waste. Novel formulations such as washing-free inks, designed to eliminate or significantly reduce post-printing rinsing steps, thereby minimizing wastewater generation and nanosphere-based systems, typically involve encapsulation of pigments within polymeric carriers to enhance fixation efficiency and reduce dye or

pigment discharge during processing, further reducing the need for post-printing washing and minimizing residual dye discharge [56].

When compared with traditional rotary screen printing, digital textile printing has been shown to offer superior environmental performance, notably lower energy and water use, and reduced waste generation. Additionally, linked strategies—such as recycling digital ink waste for screen-printing applications—demonstrate potential to further minimize resource use and environmental impact [57].

3.1.2. Economic Impact

Screen printing remains an economically attractive method for large-scale production due to its relatively low operational costs. Recent innovations have enhanced this cost-efficiency. For instance, the adoption of recycled inks and the elimination of pre-treatment and steaming steps streamline the process and reduce chemical inputs [58].

Simplified workflows and high-throughput capability make screen printing particularly suitable for mass-production settings. These characteristics not only enhance productivity but also lower labor costs, thereby supporting economic viability in competitive manufacturing environments [56].

3.1.3. Social Impact

The shift toward environmentally benign ink formulations also presents important social benefits. By replacing hazardous chemical components with non-toxic alternatives, worker exposure to harmful substances is significantly reduced, enhancing workplace safety [59].

Screen printing is increasingly leveraged in the production of functional textiles, including wearable electronics and embedded sensors. These applications open new markets and technological frontiers, driving innovation within the sector [60].

Reduced chemical usage and lower effluent volumes contribute positively to surrounding communities by improving air and water quality. Moreover, the broader adoption of sustainable practices within the textile printing industry supports long-term environmental stewardship and socially responsible production systems [57].

Despite advancements, the dominant ink type in screen printing remains plastisol, which is primarily composed of polyvinyl chloride (PVC). The environmental and health impacts of PVC are severe and well-documented. According to the Health Care Without Harm Europe study [1], it also includes additional risks associated with PVC production [7]:

- Ozone depletion through the release of carbon tetrachloride
- Contributions to climate change and environmental degradation from burning fossil fuels to produce chlorine or coal-intensive acetylene-route PVC
- Contaminating air and drinking water supplies
- Substances harmful to human health and the environment:
    - Carcinogenic vinyl chloride monomer
    - Bioaccumulative toxins, e.g., mercury, dioxins, and furans
    - Community and worker exposure to asbestos for chlorine production
    - Plastic pellets and mercury contamination of waterways from dumping chemical waste

The removable PVC-free inks developed in this research are water-based and use a binder as the primary binder and film-forming agent. Currently, the binder used is a fossil-based acrylic latex, which undermines the sustainability of the formulation despite the use of bio-based pigments, thickeners, and plasticisers. Several alternatives are being explored to replace this fossil-based component with a bio-based latex. An ongoing assess-

ment is determining whether the bio-based binder can support both ink removability and mechanical resilience. By design, the inks present a removability function.

Successfully replacing latex is central to achieving full biodegradability and compostability, which are key sustainability goals for innovation. Once the latex challenge is resolved, the current semi-bio-based formulation is expected to become fully bio-based, although this may lower the TRL due to the necessary revalidation.

3.2. Process Description for Manufacturing of Removable PVC-Free Ink

The manufacturing process for removable, PVC-free ink includes dissolving a biopolymer. Pigments, additives, and latex are then incorporated into the same reactor to complete the ink formulation. With this production, 0.5 kg of removable PVC-free ink can be produced per batch. At the laboratory scale, the developers reported no direct waste streams or emissions. Industrial-scale emission profiles remain to be evaluated.

In the current removable PVC-free ink formulation, the only non-bio-based component is the latex. Latex is the main component of the ink, serving as a binder and a film-forming material. Preliminary, this fossil-based latex can be replaced by a bio-based alternative.

During the screening assessment, the technology developers provided information on the main categories of materials used in the removable PVC-free ink formulation. At this stage of development, exact chemical names and quantities cannot be disclosed due to intellectual property protection and ongoing optimization work. This limitation constrains the ability to perform quantitative life-cycle inventory modeling and substance-level hazard classification, thereby reinforcing the qualitative and screening-level nature of the present assessment. Instead, the following categories are reported to illustrate the formulation principles:

- Pigment: Iron oxide-based inorganic pigments.
- Biopolymer: Apolysaccharide-based material serving as a structural component.
- Acrylic latex: Currently a fossil-based acrylic latex, under evaluation for replacement with bio-based alternatives.
- Additives: Cellulose-derived thickener and a bio-based plasticiser
- Water: the removable PVC-free ink is fully water-based.

The technology developers disclosed material categories but did not provide detailed selection criteria due to intellectual property constraints and ongoing optimization work. The following discussion draws on established materials science literature to contextualize the formulation and its functional components.

Iron oxide pigments are widely used in industrial coating systems due to their high chemical stability, low solubility, and comparatively favorable toxicological profile [61,62]. Their thermal stability and resistance to photodegradation make them suitable for textile applications requiring durability.

Polysaccharide-based biopolymers are commonly applied in aqueous formulations because of their film-forming capability, rheological control properties, and potential biodegradability [63,64]. In water-based systems, such biopolymers contribute to structural integrity and viscosity control during printing.

The binder (currently a fossil-based acrylic latex) plays a central role in film formation, adhesion, flexibility, abrasion resistance, and wash durability. Latex film formation depends on particle coalescence and glass transition temperature (Tg), which influence curing behavior and mechanical performance [65,66]. Textile coatings must ensure strong interfacial adhesion to fibrous substrates while maintaining flexibility under repeated deformation and laundering [67].

From a polymer adhesion perspective, introducing removability adds a competing requirement: the binder must enable controlled debonding under specific conditions without compromising in-use durability. Achieving this balance between adhesion strength and

triggered detachment represents a recognized formulation challenge [68,69] and contributes to current limitations in technology readiness and sustainability data maturity.

These material categories were subsequently mapped against the MET+Ec+S dimensions within the LCBROM framework (Table 2), linking each input to potential environmental, economic, and social implications. Although the quantitative composition is not disclosed, these categories capture the formulation's main functional components and serve as the basis for sustainability screening. Future quantitative LCA work will require full disclosure of chemical identities and proportions once the technology is at a higher TRL. Recent research highlights advances in sustainable water-based ink formulations for textile applications, confirming the growing relevance of water as a solvent system in industrial printing.

Table 2. MET+Ec+S matrix for sustainability screening of removable PVC-free ink technology.

Life Cycle Stage	Life-Cycle-Based Risks and Opportunities				
	Material	**Energy**	**Toxicity**	**Economic**	**Social**
Production	Bio-based products often place greater environmental pressure on land use and water consumption [23,24].			*Production costs may be higher because bio-based raw materials are typically more expensive.*	
	The removable, PVC-free ink is made of non-toxic components, and most of the raw materials are bio-based, making it more sustainable than the PVC-based ink. Using bio-based components can potentially reduce CO_2 emissions during production. The carbon footprint of bio-based components depends on feedstock origin, land-use impacts, and energy sources; a quantitative LCA is required to determine net emission effects. Bio-based raw materials may be sourced from agricultural residues, other by-products, and waste streams. At the laboratory scale, developers reported no direct waste streams and no emissions to air, soil, or water. Industrial-scale emission profiles remain to be assessed. The ink-removal formulation is bio-based, biodegradable, and reusable. In addition, no significant supply chain constraints for the bio-based raw materials have been identified. All raw materials used to produce the removable, PVC-free ink are sourced from within the EU. The absence of PVC reduces concerns about persistence. However, potential polymer fragmentation and microplastic release require further investigation.	Removable PVC-free ink manufacturing does not require more energy than the production of normal ink/paint. According to developer information, the removable PVC-free ink is designed to achieve comparable functional performance in terms of properties, stability, and bacteria resistance; however, full durability validation under industrial conditions remains pending.	Removable PVC-free ink uses non-toxic chemicals, unlike PVC-based ink. The bio-based components used in the removable PVC-free ink are also widely applied in other sectors, such as the cosmetics industry, where they are generally considered safe.	New market opportunity for bio-based and removable printing ink.	Workers work in a safer environment, as fewer toxic and harmful chemicals are used. Reduced risk of emissions and exposure to hazardous materials for workers. Reducing demand for unsustainable ink production in developing countries may improve working conditions for laborers.
	Bio-based latex (binder), e.g., bio-based PLA, may exhibit poor performance. *The uncertainty surrounding the bio-based content and biodegradability increases with the removable PVC-free ink.*	*Energy sources, when scaling up, require further investigation.*	*Whether there is an occupational risk associated with auxiliary materials.*		

Table 2. *Cont.*

Life Cycle Stage	Life-Cycle-Based Risks and Opportunities				
	Material	**Energy**	**Toxicity**	**Economic**	**Social**
Use	The durability of the print may be reduced, as the design can be removed relatively easily during washing.		*May produce by-products that result in undesirable performance characteristics.*	Due to higher production costs for removable PVC-free ink, the final price of printed textiles may increase for consumers. Risk for market skepticism towards removable print.	
	The removable PVC-free ink is compatible with both natural and synthetic textile materials.	Energy consumption during the printing process is not expected to change, as the removable, PVC-free ink is a drop-in solution compatible with existing printing equipment.	Only water is used as a solvent in the removal formulation.	The removable, PVC-free ink may serve as a more sustainable alternative, helping companies reduce the risk of regulatory penalties for non-compliance with sustainability policies. No additional printing equipment is required, as the ink can be substituted directly into current machines.	Using removable, PVC-free ink can reduce consumer exposure to potentially harmful substances. Furthermore, compliance with upcoming EU regulations on sustainable materials may provide companies with a competitive advantage as early adopters of the technology. Improved occupational safety may also contribute to a more positive consumer perception.
		If the removable PVC-free ink contains more water, it may require more energy to dry.			
Disposal (End-of-life)	Printed textiles may exhibit lower resistance to wear and repeated washing, potentially shortening product lifespan and leading to earlier disposal.	Current print-removal methods, such as dipping and rubbing, are largely manual and inefficient; therefore, automating this process would be necessary to improve scalability.		The removable, PVC-free ink cannot be easily distinguished from conventional printing inks, complicating sorting during recycling and potentially requiring additional labor, thereby increasing operational costs. Integration of new equipment into existing recycling facilities may also be required.	Because print can only be removed using a specific removal formulation, effective collection systems are needed to ensure that textiles are sent to appropriate recycling facilities. The effectiveness of removable PVC-free ink will largely depend on its widespread adoption across recycling infrastructure.

Table 2. *Cont.*

Life Cycle Stage	Life-Cycle-Based Risks and Opportunities				
	Material	**Energy**	**Toxicity**	**Economic**	**Social**
Disposal (End-of-life)	The PVC-free ink-removal formulation does not appear to alter the mechanical properties of the textile fibers, allowing the material to be reused after the ink is removed and the fabric is washed. This removable ink feature may therefore contribute to higher recycling and reuse rates, supporting greater circularity in textile systems. Widely adopted and effectively implemented, removability could facilitate improved recycling rates by reducing print contamination. Increased availability of recycled textile materials could lead to reduced water and other resource consumption. Furthermore, higher levels of recycling and reuse may help lower CO_2 emissions associated with textile production.		The ability to remove PVC-free ink from textiles may also help reduce the amount of textile waste sent to landfill or other disposal routes. A fully bio-based, biodegradable formulation may reduce long-term persistence in landfill environments; this assumption requires verification.		The sorting and print removal create job opportunities.
	The compostability of the removable PVC-free ink needs to be explored in the context of developing biodegradable formulations. Importantly, the removability feature is not only a functional advantage but also a recycling enabler.		*The characteristics and potential impacts of wastewater generated during the removal of PVC-free ink require further investigation. In addition, the possible release of microplastics during washing and disposal processes should be examined in more detail.*		

The suppliers of the materials listed above are from within the EU. According to the technology developers, producing removable PVC-free ink requires energy consumption similar to that of paint production.

The removable PVC-free ink can be used as a drop-in solution. Hence, it could be replaced straight with the ink used in industry. No new printing machine is needed to adopt this removable PVC-free ink formulation. The removable PVC-free ink can be applied to both cotton and synthetic materials such as polyester. However, in this research, printing on cotton textiles is of the main interest.

In this screening, cotton textiles are used as the primary reference substrate due to their dominant global market share and their relevance in mechanical and chemical textile recycling systems. However, the removable PVC-free ink can also be applied to synthetic materials such as polyester. The removable, PVC-free ink formulation has no limitations on the color range, but the colors the developers are working on are mostly red and purple.

3.3. Process Description for Manufacturing of Removal Formulation

The removal strategy is prepared by mixing a commercially available, biodegradable surfactant with water (70% of the formulation) and a carbonate-based organic solvent. The formulation enables the removal of ink from printed textiles by mechanical action, such as rubbing, after immersion in the removal solution. This facilitates the detachment of the removable PVC-free ink film, supporting textile reuse or recycling. The process is currently performed manually on a laboratory scale. Industrial automation, wastewater management,

and solvent recovery systems have not yet been validated and represent key areas for further investigation. No detailed wastewater characterization data are available at this stage.

3.4. Value Chain Mapping

The relevant value chain for removable PVC-free ink comprises several stages, as illustrated in Figure 3. It begins with sourcing the raw materials and components required for the production of removable, PVC-free ink. The ink is subsequently applied to textile substrates through a screen-printing process, typically using industry-standard equipment. The printed fabrics enter the consumer-use phase and, upon end-of-use, are ideally directed to recycling or reuse pathways—enabled by the ink's removability.

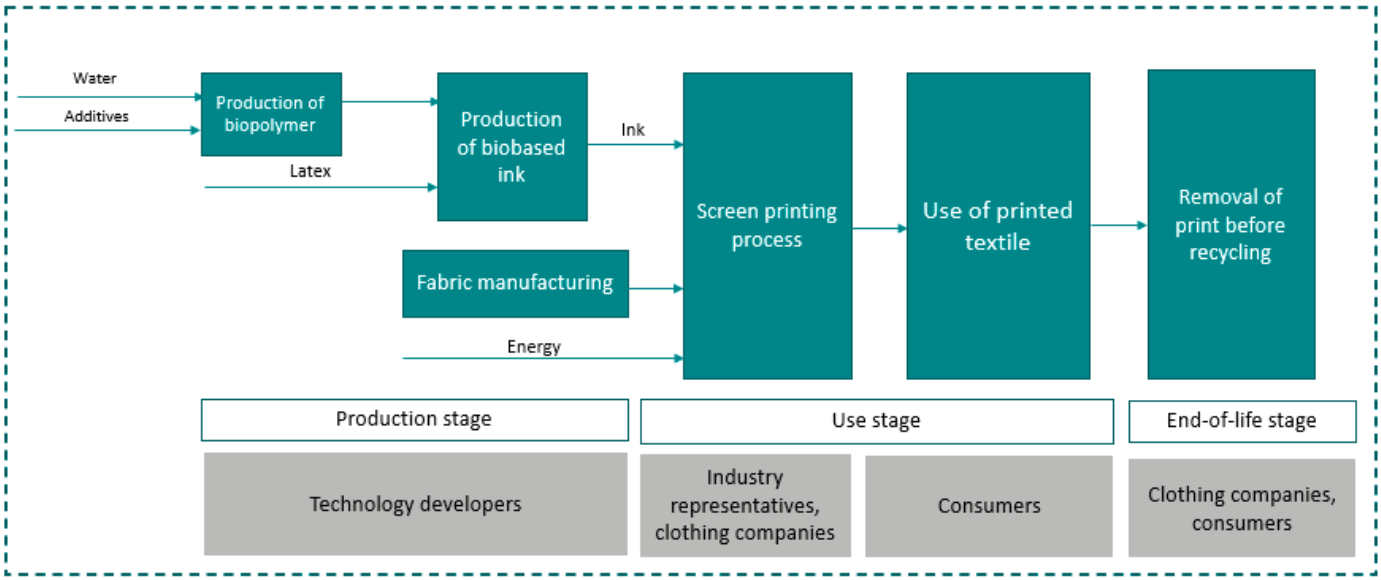


Figure 3. Mapping of the value chain of removable PVC-free ink technology, highlighting that removability enables recycling pathways that are otherwise blocked by conventional printing inks. Source: Authors' own work.

3.5. Identifying Risks and Opportunities: MET+Ec+S Matrix Evaluation

Findings from the qualitative sustainability screening for removable PVC-free ink technology, including the ink's material composition and key properties (e.g., use of bio-based pigments, fossil-based latex, cellulose-derived thickener), are systematically evaluated against environmental, economic, and social criteria and structured according to the MET+Ec+S matrix framework. The assessment identifies major risks, potential benefits, and uncertainties throughout the different life-cycle stages—production, use, and end-of-life—while considering five key dimensions: material use, energy consumption, toxicity, economic factors, and social implications, which makes explicit the link between the ink's formulation and its life cycle impacts. The entries in the matrix are derived from structured data sources, including developer-provided process information (e.g., material composition, energy demand), responses from two LCBROM questionnaires and stakeholder workshops, and supporting peer-reviewed literature. The entries in Table 2 reflect a qualitative synthesis of stakeholder input and the literature and should not be interpreted as quantified environmental performance results.

4. Discussion

The results of the MET+Ec+S matrix, developed through the LCBROM screening method and based on structured qualitative data (Table 2), where the composition of the removable PVC-free ink formulation and its removability properties are linked to measur-

able sustainability criteria, indicate that the removable PVC-free ink indicates potential sustainability opportunities compared to conventional inks such as PVC-based plastisol.

4.1. Environmental Aspects

The removable PVC-free ink and its corresponding removal formulation are primarily composed of bio-based, biodegradable materials with low toxicity profiles. Unlike plastisol inks—which are associated with hazardous chlorine-based production—toxic emissions, and microplastic release, this new formulation is designed to minimize environmental burden:

- If replaced with a fully biodegradable binder system meeting relevant compostability standards, the formulation may become compostable; this requires material-specific testing. The removal formulation is already both biodegradable and reusable.
- The absence of PVC reduces the risk of persistent microplastic generation; however, fiber and binder fragmentation under washing conditions requires experimental validation, a major environmental concern raised during stakeholder workshops.
- The carbon footprint is expected to be lower than that of plastisol inks, though this depends on the energy source used and the nature of the feedstock materials.

However, trade-offs were also identified. The use of bio-based raw materials may result in increased land and water use, which are known environmental hotspots in bio-based production systems. This impact can potentially be mitigated by sourcing biopolymers from agricultural by-products or side streams, a strategy recommended during workshop discussions.

Regarding energy, the removable PVC-free ink production process requires a similar amount of energy as conventional ink production. Yet, drying water-based inks typically demands more energy, regardless of whether the ink is bio-based or fossil-based. This nuance is essential and must be reflected in future scaling and LCA modeling.

4.2. Economic Aspects

Several economic factors were identified:

- As a drop-in solution, it is compatible with existing screen-printing infrastructure—avoiding additional capital investment.
- However, due to the use of bio-based components, production costs are currently higher, which could result in higher prices for printed textiles.
- Despite the cost increase, the removable, PVC-free ink offers regulatory and market advantages—aligning with future EU sustainability legislation and textile circularity targets.
- Market skepticism toward removable prints may still exist, highlighting the need for further demonstration and user engagement.

Cost reduction pathways include scaling production volumes, substituting specialty-grade bio-based inputs with industrial by-product streams, and optimizing binder formulation to reduce material intensity.

4.3. Social Aspects

The substitution of hazardous chemical precursors with non-toxic, bio-based ingredients offers tangible benefits for worker safety during production and printing operations. By avoiding PVC-based plastisol systems, the technology may reduce occupational exposure to substances commonly associated with PVC production and plastisol formulations, which are commonly found in PVC-based inks.

The shift away from conventional inks also has implications for improving labor conditions in supply chains, particularly in countries with less stringent chemical safety en-

forcement. This supports the broader goals of responsible sourcing and social sustainability. Additionally, safer formulations are also healthier for end-users, particularly relevant in sensitive product segments such as children's clothing.

Advances in safer formulations may also contribute to positive consumer perceptions and could play a role in future product labeling schemes or sustainability scoring systems, adding further competitive advantages. While this early-stage screening highlights clear sustainability opportunities, it also underscores the importance of addressing remaining challenges:

- Finalizing the transition to a fully bio-based binder to achieve compostability.
- Improving data availability for end-of-life and washing scenarios.
- Defining system boundaries and usage conditions for future LCA modeling.

5. Conclusions

This study presents a simplified SSbD screening of removable, PVC-free ink using the LCBROM framework. The qualitative assessment indicates potential sustainability advantages over conventional PVC-based plastisol inks, particularly in terms of a reduced hazard profile and improved compatibility with textile recycling systems through removability.

However, important trade-offs and uncertainties remain:

- Industrial-scale energy demand and emission profiles.
- Long-term durability and wash resistance.
- Polymer fragmentation and potential microplastic release.
- Wastewater management associated with removal formulation.
- Feasibility of large-scale removal infrastructure integration.

These uncertainties are intrinsic to early-stage innovation and define priority areas for future quantitative life cycle assessment, pilot-scale validation, and regulatory evaluation.

The study does not replace quantitative LCA but establishes a structured analytical basis for subsequent data generation and technology optimization within the Safe and Sustainable by Design framework.

Author Contributions: O.L.: original draft preparation, conceptualization, methodology, data curation, formal analysis, investigation; S.S. (Sahar Safarian): original draft preparation, review and editing, methodology, visualization; P.H.: data curation, formal analysis, investigation, methodology, visualization; N.E.: methodology; T.R.: methodology, supervision; M.H.: methodology; S.S. (Steffen Schellenberger): methodology; J.H.: methodology; G.U.: validation; Y.J.: validation; R.B.: validation. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Research Executive Agency (grant number 101135372).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article, except for the data from the Ecoinvent database. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: Gustav Utas and Yiming Jia were employed by Vividye AB. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that this study was funded by the BioSusTex project under grant number 101135372. The funder had the following involvement with the study: The funder had no role in the design of the study, in the collection, analysis, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

References

1. Health Care Without Harm Europe. *Annual Report 2023*; Health Care Without Harm Europe: Brussels, Belgium, 2023. Available online: https://europe.noharm.org/media/6812/download?inline=1 (accessed on 9 March 2026).
2. Wicks, Z.W., Jr.; Jones, F.N.; Pappas, S.P.; Wicks, D.A. *Organic Coatings: Science and Technology*, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2007.
3. Titow, W.V. *PVC Technology*; Springer: Dordrecht, The Netherlands, 2012.
4. Daniels, P.H. A Brief Overview of Theories of PVC Plasticization and Methods Used to Evaluate PVC–Plasticizer Interaction. *J. Vinyl Addit. Technol.* **2009**, *15*, 219–223.
5. Rahman, M.; Brazel, C.S. The Plasticizer Market: An Assessment of Traditional Plasticizers and Research Trends to Meet New Challenges. *Prog. Polym. Sci.* **2004**, *29*, 1223–1248. [CrossRef]
6. Mittal, K.L. (Ed.) *Adhesion Aspects of Polymeric Coatings*; Springer: New York, NY, USA, 2012.
7. *Kirk-Othmer Chemical Technology and the Environment, 2 Volume Set*; Wiley: Hoboken, NJ, USA, 2007; Volume 1.
8. Lithner, D.; Larsson, Å.; Dave, G. Environmental and Health Hazard Ranking and Assessment of Plastic Polymers Based on Chemical Composition. *Sci. Total Environ.* **2011**, *409*, 3309–3324.
9. Hahladakis, J.N.; Velis, C.A.; Weber, R.; Iacovidou, E.; Purnell, P. An Overview of Chemical Additives Present in Plastics: Migration, Release, Fate and Environmental Impact during Their Use, Disposal and Recycling. *J. Hazard. Mater.* **2018**, *344*, 179–199. [CrossRef] [PubMed]
10. Thornton, J. *Environmental Impacts of Polyvinyl Chloride (PVC) Building Materials*; Healthy Building Network: Washington, DC, USA, 2002.
11. Lyon, F. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans: Some Industrial Chemicals. *IARC Monogr.* **2014**, *60*, 389–433.
12. Comaniţă, E.D.; Ghinea, C.; Roşca, M.; Simion, I.M.; Petraru, M.; Gavrilescu, M. Environmental Impacts of Polyvinyl Chloride (PVC) Production Process. In *Proceedings of the 2015 E-Health and Bioengineering Conference (EHB)*; IEEE: New York, NY, USA, 2015; pp. 1–4.
13. Sevenster, A. Eco-Profiles and Environmental Declarations for PVC. *Plast. Rubber Compos.* **2008**, *37*, 403–405. [CrossRef]
14. Mersiowsky, I. Long-Term Fate of PVC Products and Their Additives in Landfills. *Prog. Polym. Sci.* **2002**, *27*, 2227–2277. [CrossRef]
15. Ragaert, K.; Delva, L.; Van Geem, K. Mechanical and Chemical Recycling of Solid Plastic Waste. *Waste Manag.* **2017**, *69*, 24–58. [CrossRef]
16. Wypych, G. *Handbook of Plasticizers*; ChemTec Publishing: Toronto, ON, Canada, 2004.
17. European Chemicals Agency. *Candidate List of Substances of Very High Concern for Authorisation*; ECHA: Helsinki, Finland, 2024. Available online: https://www.echa.europa.eu/candidate-list-table (accessed on 9 March 2026).
18. Koch, H.M.; Calafat, A.M. Human Body Burdens of Chemicals Used in Plastic Manufacture. *Philos. Trans. R. Soc. B* **2009**, *364*, 2063–2078.
19. do Paço, A.M.S. Biotechnological Tools for Plastic Waste Remediation Using Marine Fungi. Ph.D. Dissertation, Universidade de Aveiro, Aveiro, Portugal, 2024.
20. Sandin Albertsson, G.; Lidfeldt, M.; Nellström, M.; Strandberg, J.; Billstein, T.; Hammar, T.; Larsson, M. *Life Cycle Assessment of Mechanical Textile Recycling in Sweden*; IVL Swedish Environmental Research Institute: Gothenburg, Sweden, 2024.
21. Seifali Abbas-Abadi, M.; Tomme, B.; Goshayeshi, B.; Mynko, O.; Wang, Y.; Roy, S.; Kumar, R.; Baruah, B.; De Clerck, K.; De Meester, S.; et al. Advancing Textile Waste Recycling: Challenges and Opportunities across Polymer and Non-Polymer Fiber Types. *Polymers* **2025**, *17*, 628. [CrossRef]
22. Sambyal, P.; Najmi, P.; Sharma, D.; Khoshbakhti, E.; Hosseini, H.; Milani, A.S.; Arjmand, M. Plastic Recycling: Challenges and Opportunities. *Can. J. Chem. Eng.* **2025**, *103*, 2462–2498. [CrossRef]
23. Sandin, G.; Peters, G.M.; Svanström, M. Moving Down the Cause-Effect Chain of Water and Land Use Impacts: An LCA Case Study of Textile Fibres. *Resour. Conserv. Recycl.* **2013**, *73*, 104–113. [CrossRef]
24. Brizga, J.; Hubacek, K.; Feng, K. The Unintended Side Effects of Bioplastics: Carbon, Land, and Water Footprints. *One Earth* **2020**, *3*, 45–53. [CrossRef]
25. De Falco, F.; Gullo, M.P.; Gentile, G.; Di Pace, E.; Cocca, M.; Gelabert, L.; Brouta-Agnésa, M.; Rovira, A.; Escudero, R.; Villalba, R.; et al. Evaluation of Microplastic Release Caused by Textile Washing Processes of Synthetic Fabrics. *Environ. Pollut.* **2019**, *236*, 916–925. [CrossRef]
26. Garg, T.; Verma, N.; Bahl, S. Circular Textile Waste Management: Issues and Prospects. *J. Clean. Prod.* **2021**, *318*, 128585.
27. Napper, I.E.; Thompson, R.C. Release of Synthetic Microplastic Fibres from Domestic Washing Machines. *Mar. Pollut. Bull.* **2016**, *112*, 39–45. [CrossRef] [PubMed]
28. Murphy, F.; Ewins, C.; Carbonnier, F.; Quinn, B. Wastewater Treatment Works as a Source of Microplastics. *Environ. Sci. Technol.* **2016**, *50*, 5800–5808. [CrossRef]

29. Carr, S.A.; Liu, J.; Tesoro, A.G. Transport and Fate of Microplastic Particles in Wastewater Treatment Plants. *Water Res.* **2016**, *91*, 174–182. [CrossRef] [PubMed]
30. Ellen MacArthur Foundation. *A New Textiles Economy: Redesigning Fashion's Future*; Ellen MacArthur Foundation: Newport, UK, 2017.
31. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.; Hultink, E.J. The Circular Economy—A New Sustainability Paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768.
32. European Commission. *Chemicals Strategy for Sustainability: Towards a Toxic-Free Environment*; European Commission: Brussels, Belgium, 2020.
33. European Commission. *EU Strategy for Sustainable and Circular Textiles*; European Commission: Brussels, Belgium, 2022.
34. Gandini, A. Polymers from Renewable Resources: A Challenge for the Future of Macromolecular Materials. *Macromolecules* **2008**, *41*, 9491–9504. [CrossRef]
35. Azapagic, A. Developing a Framework for Sustainable Development Indicators. *J. Cleaner Prod.* **2004**, *12*, 639–662. [CrossRef]
36. Parolin, G.; McAloone, T.C.; Pigosso, D.C. What's the Catch? Trade-Off Challenges in Early Design for Sustainability. *Proc. Des. Soc.* **2024**, *4*, 1399–1408.
37. Héder, M. From NASA to EU: The Evolution of the TRL Scale in Public Sector Innovation. *Innov. J.* **2017**, *22*, 1–23.
38. *ISO 14040*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
39. *ISO 14044*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
40. Safarian, S. Environmental and Energy Impacts of Battery Electric and Conventional Vehicles: A Study in Sweden under Recycling Scenarios. *Fuel Commun.* **2023**, *14*, 100083.
41. Safarian, S. Climate Impact Comparison of Biomass Combustion and Pyrolysis with Different Applications for Biochar Based on LCA. *Energies* **2023**, *16*, 5541. [CrossRef]
42. Moni, S.M.; Mahmud, R.; High, K.; Carbajales-Dale, M. Life Cycle Assessment of Emerging Technologies: A Review. *J. Ind. Ecol.* **2020**, *24*, 52–63.
43. Arvidsson, R.; Tillman, A.; Sandén, B.A.; Janssen, M.; Nordelöf, A.; Kushnir, D.; Molander, S. Environmental Assessment of Emerging Technologies. *J. Ind. Ecol.* **2018**, *22*, 1286–1294. [CrossRef]
44. Huijbregts, M.A. Application of Uncertainty and Variability in LCA. *Int. J. Life Cycle Assess.* **1998**, *3*, 273–280. [CrossRef]
45. Heijungs, R.; Huijbregts, M.A. A Review of Approaches to Treat Uncertainty in LCA. *Environ. Sci. Technol.* **2004**, *38*, 311–317.
46. Padilla-Rivera, A.; Hannouf, M.; Assefa, G.; Gates, I. Current Application of Life Cycle Sustainability Assessment. *Environ. Impact Assess. Rev.* **2023**, *103*, 107268. [CrossRef]
47. Horgan, M.D.; Hsain, H.A.; Jones, J.L.; Grieger, K.D. Screening-Level Risk Analysis for Emerging Materials. *Sustain. Mater. Technol.* **2023**, *35*, e00524.
48. European Commission, Joint Research Centre. *Safe and Sustainable by Design (SSbD): Methodological Guidance*; Publications Office of the European Union: Luxembourg, 2024. [CrossRef]
49. Arthur, W.B. Competing Technologies, Increasing Returns, and Lock-In by Historical Events. *Econ. J.* **1989**, *99*, 116–131. [CrossRef]
50. Bergerson, J.A.; Brandt, A.; Cresko, J.; Carbajales-Dale, M.; MacLean, H.L.; Matthews, H.S.; McCoy, S.; McManus, M.; Miller, S.A.; Morrow, W.R.; et al. Life Cycle Assessment of Emerging Technologies. *J. Ind. Ecol.* **2020**, *24*, 11–25. [CrossRef]
51. Cucurachi, S.; van der Giesen, C.; Guinée, J. Ex-Ante LCA of Emerging Technologies. *Procedia CIRP* **2018**, *69*, 463–468. [CrossRef]
52. Thonemann, N.; Schulte, A.; Maga, D. Prospective Life Cycle Assessment for Emerging Technologies. *Sustainability* **2020**, *12*, 1192. [CrossRef]
53. European Commission, Joint Research Centre. *Safe-and-Sustainable-by-Design (SSbD) Framework*; JRC: Luxembourg, 2022.
54. van Dijk, J.; Flerlage, H.; Beijer, S.; Slootweg, J.C.; van Wezel, A.P. Safe and Sustainable by Design: A Computer-Based Approach to Redesign Chemicals. *Chemosphere* **2022**, *296*, 134050. [CrossRef]
55. Kärnman, T.; Schellenberger, S.; Gottfridsson, M.; Halling, M.; Johansson, K.; Rydberg, T.; Hildenbrand, J. Life Cycle Based Risk and Opportunity Mapping: A Systematic Collaborative Procedure to Integrate Environmental and Health Aspects in Early Innovation as Possible Pre-Screening to the Safe and Sustainable by Design Assessments. *ChemRxiv* **2025**. [CrossRef]
56. Safarian, S.; Lysenko, O.; Elginoz, N.; Rydberg, T.; Halling, M.; Schellenberger, S.; Hildenbrand, J.; Hummel, M.; Tarhini, A.A.; Reyes Forsberg, D.C.; et al. Sustainability screening of closed-loop textile recycling: Addressing innovation risks and opportunities from environmental, economic, and social perspectives. In Proceedings of the Joint 17th International Green Energy Conference (IGEC-XVII) & 6th International Conference on Energy and AI (ICEAI-VI) & 6th Arctic Energy Forum, IGEC2025-045, Reykjavik, Iceland, 12–15 October 2025.
57. Shukla, D.; Liu, Y.; Zhu, Y. Eco-Friendly Screen Printing of Silver Nanowires for Flexible and Stretchable Electronics. *Nanoscale* **2023**, *15*, 1225–1233. [CrossRef]
58. Hoque, S.; Chapman, L.; Moore, M.; Lavelle, J.; Saloni, D.; Woodbridge, J.; King, K. Environmental Sustainability Analysis of Rotary-Screen Printing and Digital Textile Printing. *AATCC J. Res.* **2024**, *11*, 464–473. [CrossRef]

59. Lin, X.; Li, X.; Zhang, Z.; Li, X.; Zhang, W.; Xu, J.; Song, K. Screen-Printed Water-Based Conductive Ink on Stretchable Fabric for Wearable Micro-Supercapacitor. *Mater. Today Chem.* **2023**, *30*, 101529. [CrossRef]
60. Pan, K.; Fan, Y.; Leng, T.; Li, J.; Xin, Z.; Zhang, J.; Hao, L.; Gallop, J.; Novoselov, K.; Hu, Z. Sustainable Production of Highly Conductive Multilayer Graphene Ink for Wireless Connectivity and IoT Applications. *Nat. Commun.* **2018**, *9*, 5197. [CrossRef]
61. Gorjanc, M.; Gerl, A.; Kert, M. Screen Printing of pH-Responsive Dye to Textile. *Polymers* **2022**, *14*, 447. [CrossRef] [PubMed]
62. Cornell, R.M.; Schwertmann, U. *The Iron Oxides: Structure, Properties, Reactions, Occurrences and Uses*, 2nd ed.; Wiley-VCH: Weinheim, Germany, 2003.
63. Buxbaum, G. (Ed.) *Industrial Inorganic Pigments*, 3rd ed.; Wiley-VCH: Weinheim, Germany, 2008.
64. Thakur, V.K.; Thakur, M.K. Processing and Characterization of Natural Cellulose Fibers/Thermoset Polymer Composites. *Carbohydr. Polym.* **2014**, *109*, 102–117. [CrossRef]
65. Rhim, J.W. Physical and Mechanical Properties of Water-Resistant Sodium Alginate Films. *LWT–Food Sci. Technol.* **2004**, *37*, 323–330. [CrossRef]
66. Keddie, J.L. Film Formation of Latex. *Mater. Sci. Eng. R* **1997**, *21*, 101–170. [CrossRef]
67. Winnik, M.A.; Yekta, A. Associative Polymers in Aqueous Solution. *Curr. Opin. Colloid Interface Sci.* **1997**, *2*, 424–436. [CrossRef]
68. Holme, I. Innovative Technologies for High Performance Textiles. *Color. Technol.* **2007**, *123*, 59–73. [CrossRef]
69. Kinloch, A.J. *Adhesion and Adhesives: Science and Technology*; Springer: Dordrecht, The Netherlands, 2012.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.