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Status Quo Analysis Textile Sector

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Executive Summary

The ECHT (Enable Digital Product Passports with Chemicals Traceability for a Circular Economy) status quo analysis report examines the current state of chemical traceability in the textile and carpet industries, revealing a complex interplay between stakeholders, regulatory frameworks, and market dynamics. The overarching goal is to build the foundations for effective training schemes that support the adoption of Digital Product Passports (DPPs) in line with the European Union's 2027 transparency and traceability goals.

Our analysis employs nine complementary frameworks to understand chemical traceability implementation challenges. These nine analytical frameworks converge to reveal key insights about chemical traceability implementation. The complexity of chemical management becomes evident in the need to track approximately 12,000 different chemicals throughout production processes, with particular concerns surrounding substances such as azo dyes, PFAS, phthalates, and various processing agents (Bour et al., 2023), (Swedish Chemicals Agency, 2014). Current gaps in REACH registrations and information requirements highlight the need for more comprehensive solutions. The evident disparities between large corporations and SMEs emerge as a significant challenge, particularly given that SMEs represent 89% of textile companies in the NWE region (Di Bella et al., 2023). Implementation capabilities vary widely across organisations, affecting their ability to adopt and maintain traceability systems effectively. Regulatory requirements, including REACH and ESPR, create a complex compliance environment that organisations must navigate. This regulatory landscape intersects with market pressures, where consumer demand for sustainable products creates competitive advantages while complex supply chains and resource constraints pose implementation challenges.

To address these challenges, we propose comprehensive training schemes that acknowledge the diverse needs of stakeholders while ensuring an inspiring narrative about traceability objectives. These schemes must select participants representing various roles and value chain positions, structure workshops to build common understanding, and provide continuous development opportunities. Content should be tailored to role-specific needs, from technical implementation to policy development and stakeholder engagement.

Our analysis culminates in the identification of five fundamental dimensions that shape successful implementation of chemical traceability: systemic approach, training and capacity building, technology adoption, policy frameworks, and market dynamics. Progress in this transformation requires coordinated action across all five dimensions. Through this integrated approach, the textile and carpet industries can make significant strides toward greater transparency and sustainability, ultimately contributing to the circular economy objectives of the European Green Deal while maintaining their distinct sector characteristics and requirements.

1. Introduction

1.1. Background and Objectives

The ECHT (Enable Digital Product Passports with Chemicals Traceability for a Circular Economy) project emerges at a critical moment in the European Union's transition toward a circular economy, specifically addressing the challenges in textile and carpet sectors. With approximately 6 million tonnes of textiles discarded annually in the EU - roughly 11 kg per person, according to the report (European Environmental Agency, 2023), particularly concentrated in the wealthy North-West Europe (NWE) region, there is an urgent need for systemic change in how these industries manage their chemical content and material flows.

The status quo analysis aims to establish a solid foundation for an efficient and transformative learning process in chemical traceability within the textile and carpet sectors. This analysis seeks to understand the complex interplay between technical capabilities, organisational readiness, and systemic barriers that industry actors face when implementing chemical traceability systems.

Drawing on the expertise of ECHT project partners, associated organisations and on desk research, the analysis examines how different actors currently approach traceability challenges. What makes this analysis particularly valuable is its focus on the practical realities faced by the textile system including small and medium-sized enterprises, which represent the vast majority (89%) of textile companies in the NWE region (Di Bella et al., 2023). These SMEs often face unique challenges in implementing new systems, from limited resources to complex supply chain relationships.

By understanding these nuances, we can ensure that the resulting training schemes address the technical aspects of traceability and also the organisational and cultural changes needed for successful implementation. The research methodology for this report followed a stepwise analytical process to examine chemical traceability in the textile and carpet industries. The investigation began with a review of the current state of chemical use and management systems, establishing a foundational understanding of existing practices and frameworks.

Our analytical approach progressed through three main phases. **The first phase** involved a systematic examination of chemical management systems, release mechanisms, and regulatory frameworks, documented in Section 2. This was accomplished through literature review, industry documentation analysis, and examination of current chemical management practices. **The second phase**, detailed in Section 3, employed analytical frameworks to assess market dynamics, implementing a structured evaluation of both drivers and barriers affecting chemical traceability implementation. **The third phase**, presented in Section 4, utilised system mapping frameworks to analyse the complex interrelationships between regulatory requirements, market forces, and industry practices in both textile and carpet sectors.

The methodology incorporated comparative analysis techniques and several frameworks to examine the distinctions between textile and carpet industry practices, particularly evident in Section 4.3's system map analysis. Data collection methods included document analysis, regulatory framework review, and assessment of industry practices. This methodological approach enabled the identification of key patterns and systemic relationships.

1.2. The ECHT Project in a Nutshell

The ECHT project employs an integrated methodological approach that combines theoretical analysis with active industry engagement. While desk research provides the foundation for understanding chemical traceability, direct collaboration with industry stakeholders through reflective sessions and participatory workshops enriches this knowledge generation with practical insights. At the heart of this approach lies the development of a comprehensive traceability strategy, which establishes a common framework for understanding and implementing chemical traceability across textile value chains. This strategy emerges from the systematic knowledge sharing among project partners and associated organisations, including civil society, each contributing unique perspectives from different segments of the value.

The project research methodology particularly emphasises identifying and understanding various impediments to traceability implementation across different scales of operation. As mentioned previously, this includes examining technical barriers, organisational challenges, and systemic issues that need to be addressed in the training schemes. This methodological framework is designed to create a solid foundation for developing targeted training schemes that can effectively support the industry's transition toward comprehensive chemical traceability, ultimately enabling the successful implementation of Digital Product Passports (DPPs) and supporting the broader goals of the European Green Deal.

2. Understanding Chemical Traceability in the Textile Industry

2.1. Current State of Chemical Use in Textiles

In the context of textiles, chemical traceability refers to the ability to track and trace substances used in textile articles throughout the supply chain. This involves ensuring that all chemicals involved in the production process are documented and can be traced back to their origin (Schenten et al., 2019).

For the purpose of our analysis, we will not take the post-consumer phase into account. This decision is aligned with the objectives of the ECHT project, which focuses on chemical traceability and Digital Product Passport implementation. This approach allows us to explore the necessary infrastructures and systemic requirements for integrating chemical transparency into textile manufacturing and supply chains. By defining these structural elements upfront, we create a foundation that can later support broader traceability strategies, including those addressing post-consumer waste streams.

The textile industry faces significant challenges in managing and tracking chemical substances across its global supply chain. Textile production involves a vast array of chemicals — approximately 12,000 have been identified in manufacturing processes (Bour et al., 2023), (Swedish Chemicals Agency, 2014). Many of these chemicals may qualify as substances of concern (SoC) under the European Union's Ecodesign for Sustainable Products Regulation (ESPR), necessitating stricter oversight.

The scale of chemical use in textiles is striking. Research estimates that producing just one kilogram of cotton T-shirts requires around three kilograms of chemicals (Hurwicz, 1979; Swedish Chemicals

Agency, 2014). This figure specifically applies to the processing stage, covering all chemicals used to transform raw cotton into a finished garment, including dyeing, finishing, and treatment for specific properties. However, it excludes pesticides and fertilisers used during cultivation, as well as biocides applied during distribution. This highlights the intensive use of chemicals in post-harvest manufacturing processes.

Several major chemical categories raise particular concerns due to their environmental and health risks. Dyes and colorants, especially azo dyes, are widely used in textiles but pose significant health risks (Swedish Chemicals Agency, 2014). These dyes can degrade into aromatic amines and quinoline, which have been linked to carcinogenic effects, particularly through skin contact (Antal et al., 2016). Some azo dyes, especially direct and acid azo dyes, undergo a process called reductive cleavage in the human body, breaking down into aryl amines — many of which are known carcinogens (cancer-causing). This breakdown can occur in the liver, through intestinal bacteria, or even via skin bacteria.

Despite regulatory restrictions, concerns persist. Approximately 25% of the azo dyes listed in the Colour Index database (around 500 dyes) are synthesised using carcinogenic amines already regulated under REACH (Swedish Chemicals Agency, 2014). While technically restricted, these dyes continue to appear on the market, as they remain listed with suppliers. Adding to the hazard, both direct and acid azo dyes bind weakly to textile fibers, making them more likely to transfer onto skin or enter the body through ingestion — posing particular risks to young children.

Surface treatment chemicals, particularly per-and polyfluoroalkyl substances (PFAS), represent another pressing concern. Textiles account for roughly 35% of global fluoropolymer demand, making them the largest contributor to PFAS pollution in Europe (Doyle et al., 2024). Valued for their water, oil, and stain resistance, PFAS compounds are now under intense regulatory scrutiny due to their environmental persistence and serious health risks. These risks include endocrine disruption, reproductive toxicity, cancer, and organ damage (Doyle et al., 2024). The presence of perfluorinated and polyfluorinated alkyl substances (PFAS), known as "forever chemicals" or "eternal chemicals", is recognised as a particularly urgent challenge to be addressed (European Environmental Agency, 2019). Comprising more than 4,700 chemicals, PFAS are extremely persistent in the environment and human bodies, accumulating over time and potentially leading to serious health problems including liver damage, thyroid disease, obesity, fertility issues, and cancer (Peritore et al., 2023). The Organisation for Economic Co-operation and Development (OECD) has significantly expanded the scope of PFAS classification through its revised definition, which now includes any chemical containing at least one saturated CF2 or CF3 moiety.

This broader definition has dramatic implications for chemical identification and management, as evidenced by PubChem, one of the largest open chemical databases, where over 7 million compounds — out of its 116 million total compounds — are now classified as PFAS under these new criteria (Schymanski et al., 2023). This expansive reclassification exemplifies the widespread presence of PFAS in chemical compounds and reveals the growing challenge of managing these substances effectively.

The industry also employs various processing chemicals including phthalates as plasticisers and formaldehyde in fabric finishing. Studies have consistently linked these substances to potential health risks (Rovira and Domingo, 2019); (Antal et al., 2016). Additional processing agents like chlorophenols and alkylphenol ethoxylates present further environmental and toxicity concerns.

The extensive use of hazardous chemicals in textile manufacturing reinforces the urgent need for stronger chemical management throughout the supply chain. Addressing these challenges requires enhanced traceability, stricter regulations, and industry-wide commitment to safer alternatives.

2.2. Chemical Management Systems and Traceability Frameworks

Taking into consideration this context, management systems must track not only the approximately 12,000 different chemicals potentially used in production but also account for their transformations, interactions, and potential breakdown products. The persistence of PFAS exemplifies why such comprehensive tracking is crucial - these substances remain in the environment indefinitely, making their traceability throughout the supply chain essential for protecting both human health and the environment.

Ideally, an effective chemical management system needs to integrate multiple dimensions: substance identification and tracking, hazard assessment and risk management, regulatory compliance monitoring, and information sharing along the value chain. This systemic approach becomes particularly crucial when considering that the production of just one kilogram of cotton textiles involves three kilograms of chemical substances, each with its own hazard profile and regulatory requirements. Furthermore, managing PFAS as a single chemical class is necessary due to their high persistence, accumulation potential, and potential hazards, emphasizing the need for safer alternatives and environmental removal methods. (Kwiatkowski et al., 2020)

The significant presence of, for example, harmful and highly persistent chemicals, coupled with the intensive chemical usage in textile production, substantiates why the industry must transition from simple chemical inventory management to sophisticated traceability systems that can effectively monitor and control these complex chemical interactions throughout the supply chain.

For reference, chemical inventory management in the textile industry represents a systematic approach to handling, tracking, and controlling chemicals throughout their lifecycle in textile production. As described by (Roos et al., 2019), it incorporates comprehensive life cycle inventory frameworks to model chemical products and their emissions, while enabling environmental impact assessments. The system extends beyond simple tracking to include function-based management approaches that help retailers identify and substitute hazardous substances (Roos et al., 2020). According to (Ivy, 2021), effective chemical management relies on well-established systems that include restricted substance lists (RSL) and manufacturing restricted substance lists (MRSL), while facilitating communication across complex global supply chains to ensure compliance with legal and customer demands (Jönsson et al., 2021).

Building on this rationale, the development of comprehensive chemical traceability systems must go beyond tracking currently used substances. It should also consider their long-term persistence, presence in products made from recycled materials, potential future identification of harmful effects, and associated health risks. These complex interactions between chemicals and their long-term effects are visualized in Figure 1, which maps out the immediate health impacts, environmental consequences, and delayed effects that can emerge from chemical exposure in textiles.

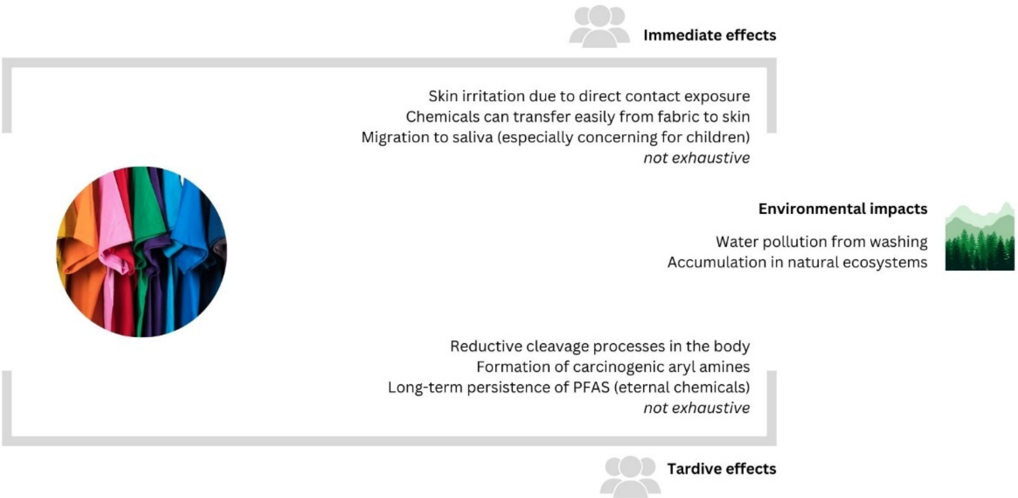

Figure 1: Overview of potential chemical exposure pathways and
their immediate and long-term effects on human health and ecosystems.

As advanced before, Chemical Management Systems (CMS) provide a structured approach to monitor and control chemicals throughout the textile production process. According to the (Camera Nazionale della Moda Italiana, 2021) report, effective CMS implementation requires clear documentation, including safety data sheets and detailed production records, enabling full traceability of chemicals in raw materials, semi-finished goods, and final products.

In addition to that, as mentioned previously, the traceability framework must account for the entire lifecycle of chemical substances in textiles along the value chain. This includes documentation of initial chemical inputs, tracking of transformations during production processes, and monitoring of residual chemicals in finished products and media, such as effluent, water, air and soil.

The implementation of Chemical Management Systems must explicitly address how chemicals can be released from textiles, production, recycling and disposal processes and potentially expose humans and the environment. Understanding these pathways — from initial manufacturing processes through product use, recycling and disposal — is crucial for effective chemical management. This tracking becomes particularly important when considering multiple exposure routes including direct skin contact, environmental releases during washing, and indoor air quality impacts. By incorporating exposure pathway analysis, including occupational exposure and exposure of communities close to production and recycling facilities, landfills and incinerators into CMS documentation and monitoring procedures, organisations can better assess risks, implement appropriate controls, and ensure their chemical traceability systems effectively protecting both human health and the environment. This holistic approach to chemical management and exposure prevention, including the phase-out and substitution of harmful chemicals with safe alternatives, represents a key step toward more sustainable textile production practices.

2.3. The Release Mechanisms and Exposure Pathways

Chemical substances in textile materials production, recycling and disposal processes can be released through multiple mechanisms including migration, leaching, evaporation, and particulate releases.

These release patterns depend on the inherent chemical and/or physical properties of the substance, its incorporation method into the textiles, fiber type, and handling patterns.

Three primary exposure routes have been identified through research. Direct skin contact represents the predominant exposure pathway, with studies documenting that substances like benzothiazoles and certain dyes can penetrate the skin (Ladaresta et al., 2018). Environmental release forms a second major pathway — (Swedish Chemicals Agency, 2014) estimates that between 2,000-22,000 kg of hazardous acid dyes and direct dyes are annually released to wastewater in the EU from textile washing alone. Wastewater treatment plants cannot destroy PFAS with the added problem that the treatment process can generate higher PFAS concentrations in the effluent (Schymanski et al., 2023). Indoor air quality constitutes the third significant exposure route, as textiles comprise the largest surface area in indoor environments, creating substantial potential for chemical releases through evaporation and dust particles. Understanding these exposure pathways requires examining the specific mechanisms through which chemicals move from textiles to humans and the environment. Figure 2 represents the four mentioned distinct release mechanisms — migration, leaching, particulate release, and evaporation — each contributing to different exposure scenarios.

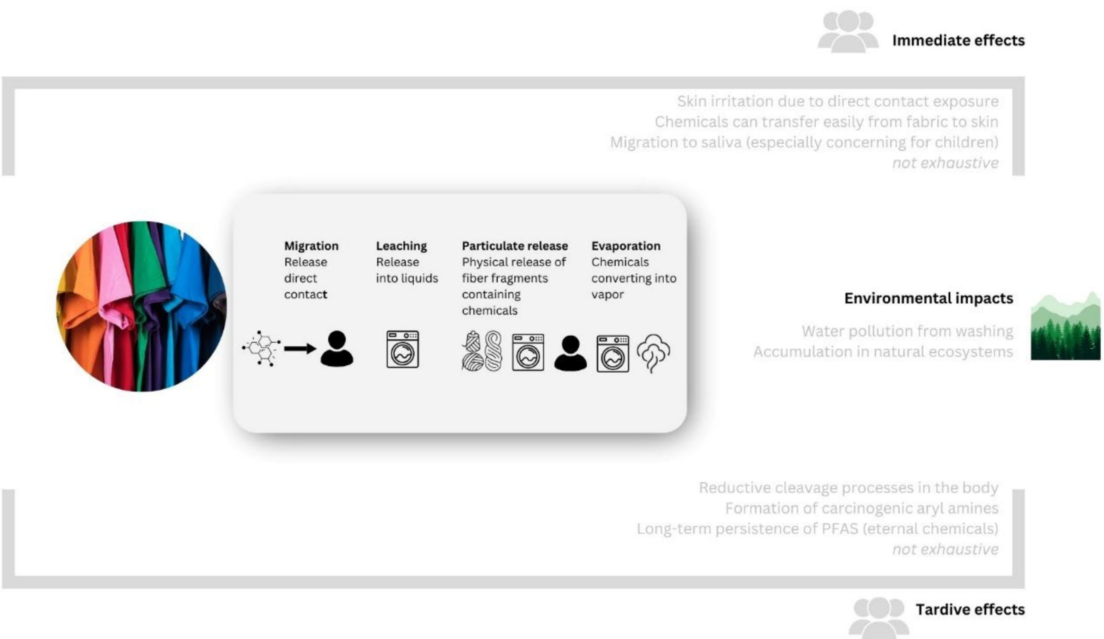

Figure 2: Chemical release mechanisms from textiles and their associated pathways for human and environmental exposure.

In light of these findings, the environmental footprint of textiles is most significant during production and end-of-life stages, with manufacturing processes and waste management presenting greater environmental challenges highlighting the need for comprehensive solutions that address the entire lifecycle of textile products.

2.4. The Regulatory Framework

The current regulatory framework, particularly in the EU, centres on REACH and the upcoming ESPR requirements. However, significant challenges exist in implementation. According to the (Swedish

Chemicals Agency, 2014) report, textile articles consumed in the EU, of which approximately 80% are imported from non-EU countries, include a wide variety of categories such as clothing, household items, and other related goods. Carpets are explicitly mentioned as a part of the household textile category, dominating this segment with a 38% market share. Even though there are existing mechanisms, such as REACH Article 33 (SVHC information on articles) or pending obligations, such as the Digital Product Passport under ESPR, information availability, especially in imported articles, is inherently scarcer.

Data availability under REACH presents a complex challenge for chemical traceability in textiles. Of approximately 3,500 substances identified as relevant for textile use, about 2,000 remain unregistered under REACH for various reasons, which poses a potential compliance issue (Swedish Chemicals Agency, 2014). Some substances may fall below REACH's one-tonne annual threshold for registration requirements, while others might be classified as intermediates or fall under other specific regulatory categories. This registration gap should not be interpreted solely as a potential compliance issue, but rather as a reflection of REACH's structured approach to chemical registration, which includes various thresholds and exemptions. Furthermore, current REACH information requirements for articles only cover Substances of Very High Concern (SVHC) listed on the Candidate list, leaving out many potentially harmful substances, including most sensitizing chemicals. This combination of registration thresholds and limited information requirements for articles creates challenges for comprehensive chemical traceability in the textile sector.

2.5. Advancing Chemical Traceability in the Textile Industry

Technological solutions for implementing chemicals traceability in the textile and carpets industries are crucial for ensuring sustainability and compliance with legal and societal demands. Current state-of-the-art solutions include blockchain technology, flexible SERS substrates and Internet of Things.

The blockchain technology is increasingly used for supply chain traceability in the textile and apparel industries as it offers a secure and transparent way to track products from raw materials to finished goods, ensuring product authentication and supply chain sustainability.

The Lenzing Group, a leading fiber producer, has adopted blockchain technology to enhance traceability, addressing the growing demand for transparency in supply chains, although challenges remain in its full implementation (Ahmed, 2021). Complementing such advancements, flexible SERS (surface-enhanced Raman scattering) substrates are being employed to detect hazardous materials, such as chemicals in textiles, further supporting efforts to ensure safety and sustainability across the textile value chain. These substrates, made from materials like fabrics and polymer nanofibers, enable practical, on-field applications due to their low cost and ease of use. They are particularly effective for trace detection of dyes and other chemicals in textiles (Bharati and Soma, 2021). Finally, the integration of Internet of Things (IoT) technologies for remote monitoring and control of water quality in textile manufacturing is another emerging solution. These systems can help manage the removal of dyes and chemicals from wastewater, although a common platform for integrating traditional and modern treatment methods is still lacking (Hynes et al., 2020).

While these technological solutions for chemical traceability are burgeoning in the market, this analysis deliberately maintains a technology-agnostic approach in alignment with the ECHT project's scope and objectives. This position addresses chemical traceability focusing on organisational readiness, stakeholder collaboration, and systemic understanding. By focusing on the underlying principles, barriers, and enablers of traceability rather than specific technical solutions, we ensure that our findings and recommendations remain relevant regardless of technological evolution or market preferences. This approach also aligns with the project's goal of creating inclusive solutions that work for organisations of all sizes and technical capabilities, particularly considering that 89% of textile companies in the NWE region are SMEs (Di Bella et al., 2023) with varying levels of technological maturity and resources. The emphasis therefore remains on establishing the foundational elements of successful traceability implementation, allowing organisations to select and adapt technological solutions that best fit their specific contexts and capabilities. However, a globally harmonised system would best accommodate the needs of seamless information flow and avoidance of multiple reporting requirements.

The barriers and the lack of incentives in the textile supply chains, create significant challenges for chemical traceability and information flow. Implementing effective chemical management in this context requires key practices and considerations, particularly for small and medium-sized enterprises (SMEs) seeking to enhance their environmental performance.

Literature suggests that SMEs should prioritise both reducing chemical usage and substituting hazardous chemicals with environmentally friendly alternatives, as these strategies have shown impressive results. Studies demonstrate that such practices can achieve 15-32% reductions in chemical use alongside 13-37% reductions in chemical oxygen demand in wastewater (Ozturk et al., 2020) . Given the complex chemical composition of textile wastewater, effective treatment remains crucial, with advanced oxidation processes (AOPs) and biological treatments emerging as promising solutions that can be combined to manage and recycle process water efficiently (Paździor et al., 2019).

Smart environmental management practices (SEMPs) offer SMEs effective strategies to reduce pollution and resource consumption through low-cost, high-return approaches that deliver significant savings in water, chemicals, and energy while simultaneously reducing greenhouse gas emissions (Kumar et al., 2022). To enhance these efforts, a function-based approach to life cycle management (LCM) empowers SMEs to manage and substitute hazardous chemicals effectively by providing tools that simplify chemical information for non-chemists and foster continuous knowledge sharing among stakeholders (Roos et al., 2020). Complementing these management strategies, SMEs must navigate regulatory restrictions on specific chemicals, such as endocrine-disrupting surfactants, while understanding the associated financial and technical risks alongside the benefits of compliance to ensure effective chemical management (Ho and Watanabe, 2020).

Successful chemical management in textile SMEs requires a holistic strategy combining hazardous chemical reduction and substitution, effective wastewater treatment, smart environmental practices, and regulatory compliance. While these approaches deliver tangible financial and operational benefits that support the transition toward sustainable production, their implementation faces significant challenges. Notably, transparency within supply chains is hindered by technical capacity limitations, inconsistent global standards, and supplier reluctance to disclose proprietary formulations. To address these barriers, emerging solutions such as incorporating chemical information into ecolabelling and leveraging digital tools like RFID tags show promise in enhancing chemical visibility across supply chains.

However, as long as transparency and traceability regarding chemical composition information remain optional, companies, including SMEs, may find it challenging to obtain the necessary details from upstream suppliers. They may be too small for suppliers to take their information requests seriously. If the supplier is located in another jurisdiction, demanding transparency from upstream can be even more difficult. Consequently, a growing number of companies advocate for the establishment of mandatory globally harmonised transparency and traceability systems and standards that save time and money for businesses while protecting their brand reputations and levelling the playing field in trade.

2.6. Unveiling the Weak Links

The complex landscape of chemical traceability in the textile industry reveals significant gaps and challenges that require systematic attention, as demonstrated by this overarching analysis using the SWOT and Ishikawa tools. The assessment shows an imbalanced situation where weaknesses and threats currently outweigh strengths, particularly evident in the information asymmetries, registration gaps, and limited transparency of imported products that make up 80% of EU textile consumption.

However, the analysis also reveals substantial opportunities for transformation through growing market demands, emerging technologies, and potential for harmonised systems. The combination of EU support programs, increasing technological capabilities, and push for circular economy initiatives provides a strong foundation for addressing current challenges. This suggests that while the industry faces significant hurdles in chemical traceability implementation, there exists a clear pathway for development through coordinated action, technological adoption, and systematic capacity building, particularly focused on supporting SMEs and creating harmonised global standards.

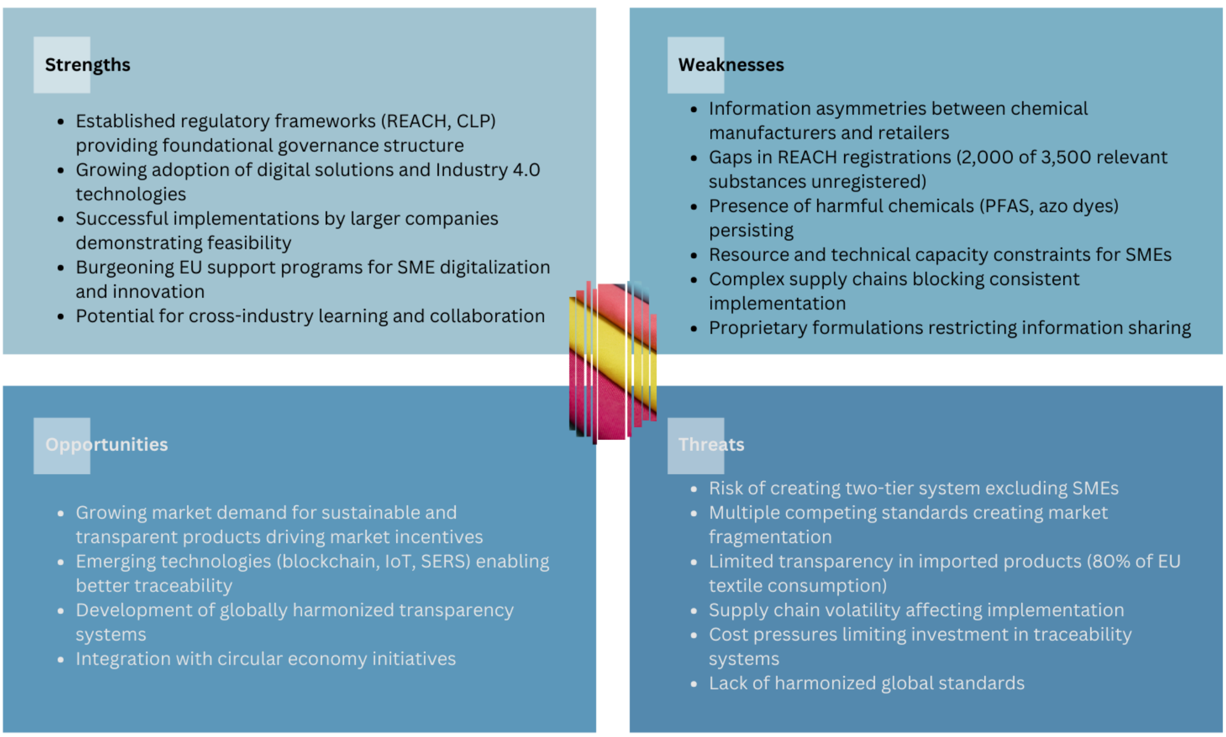

Figure 3: SWOT analysis

The Ishikawa analysis reveals six key dimensions contributing to low chemical traceability in the textile industry, highlighting both technical and systemic challenges. The analysis demonstrates how interrelated factors across people, methods, data, processes, context, and production create a complex web of obstacles. Notably, the data and process dimensions emerge as particularly critical, with information asymmetries and complex global supply chains creating fundamental barriers to effective traceability implementation.

Examining the relationships between these dimensions uncovers how limitations in one area amplify challenges in others. For instance, the people dimension's limited technical expertise compounds the difficulties posed by complex methods and data requirements, while production complexity intensifies the challenges of process standardisation. The context dimension, particularly the high proportion of imports from non-EU countries (80%), exacerbates these challenges across all other dimensions. This interconnected nature of the barriers suggests that successful interventions must address multiple dimensions simultaneously rather than focusing on isolated solutions.

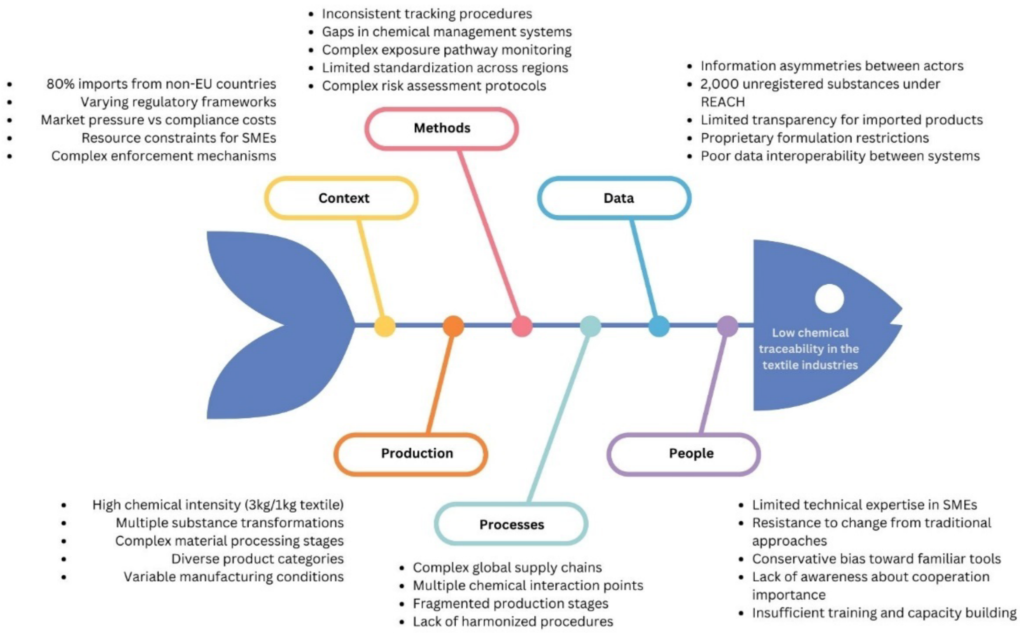

Figure 4: Ishikawa analysis

In sum, the textile industry's chemical traceability challenges require a comprehensive approach combining harmonised regulation, enhanced value chain communication, and continued research into chemical hazards, exposure pathways and safe alternatives. Future efforts must focus on developing more robust tracking systems, expanding chemical registration requirements, and improving information flow throughout the global supply and value chain.

As mentioned previously, Internet of Things (IoT) and emerging sensor technologies and digital solutions for data gathering offer promising avenues for improving traceability. However, their successful implementation will require coordinated action across the industry, including standardisation and harmonization of approaches and increased support for SMEs. Policy development should focus on closing regulatory gaps, particularly for imported articles, while fostering innovation in safer chemical alternatives and traceability solutions.

The integration of chemical management best practices from frameworks like the (Camera Nazionale della Moda Italiana, 2021), combined with specific measures to address challenges posed by substances of concern and high concern, will be crucial for moving the industry toward safer chemical use and enhanced environmental stewardship. Achievement in this transformation will require sustained commitment from all stakeholders in the textile value chain.

3. Analysis of Incentives and Impediments in Chemical Traceability

3.1. Understanding Chemical Traceability Through Multiple Analytical Lenses

Chemical traceability in the textile industry demands analysis through multiple theoretical lenses to capture its complexity. Nine distinct frameworks reveal the interplay between market dynamics, organisational behavior, and institutional structures in shaping traceability implementation and outcomes.

The Comparative Economic Systems framework (Hurwicz, 1979) examines how market structures influence information sharing in decentralised systems, particularly relevant when chemical manufacturers possess detailed knowledge but may lack transparency incentives. Swiss's **Results-Based Management** framework (Swiss, 2005) emphasises timing and political context, highlighting how program success depends on balancing immediate implementation costs against long-term benefits. The **Multiple Incentive System** framework (Paulson, 1981) reveals why technical solutions often fail without addressing underlying social and economic conditions, while the **Institutional Economics** framework (Bertone and Meessen, 2013) explains how formal and informal institutions affect system performance across different contexts.

Contemporary research is expanding this and proposing innovative approaches to address the stakeholder dynamics. **Evolutionary Game Theory** (Fan and Hui, 2020), (Zhou et al., 2019) models how stakeholders adapt their strategies over time, demonstrating that dynamic policies targeting multiple stakeholders achieve more stable outcomes than static interventions. The **Institutional Perspective** integration with this approach (Zhou et al., 2022) further reveals how organisational structures influence cooperation patterns and sustainability outcomes.

Principal-Agent Theory (Wang and Song, 2021) specifically addresses information asymmetry challenges by guiding the design of incentive systems that will potentially motivate accurate information sharing between suppliers and brands. Complementing this, the **Comparative Analysis of Game Structures** framework (Nielsen et al., 2019) and the **Systems-based** framework (da Costa Junior et al., 2019) takes a broader view, examining how different incentive policies and procurement decisions affect social welfare and environmental outcomes across the supply chain. This approach has revealed that traceability outcomes are highly sensitive to the underlying game structure, suggesting that policy design must carefully consider how different stakeholders interact and compete within the system.

This multi-framework analysis demonstrates that successful chemical traceability requires a holistic approach. Effective implementation must address technical and socio-economic factors while considering institutional contexts and stakeholder incentives. The key lies in creating systems that align stakeholder interests, manage information asymmetries, and adapt to the evolving market conditions.

Moving from theoretical frameworks to practical application, the textile industry's market structure presents several key challenges for traceability implementation.

3.2. Market Structure and Economics

In the background, the textile industry's market structure creates significant challenges for chemical traceability implementation. The (Swedish Chemicals Agency, 2014) analysis reveals that approximately 80% of EU-consumed textiles are imported, creating substantial information asymmetries between producers and consumers.

The integration of environmental considerations into economic decision-making remains inadequate, presenting significant challenges in implementing traceability and addressing externalities. While various methods exist to bridge this gap, the underlying practices and drivers of decision-making reflect a complex interplay of factors. This challenge is particularly evident in supply chain dynamics, where (Wiesmeth and Häckl, 2015) demonstrate how inadequate environmental integration complicates traceability implementation, with price mechanisms often failing to account for environmental and health externalities, thereby creating misaligned incentives throughout the supply chain.

Organisations currently integrate environmental considerations primarily through monetary valuation methods, including economic consequences assessment, mitigation and restoration costs, and willingness-to-pay analyses. Though these methods aim to quantify environmental impacts in economic terms, their variability can significantly influence decision-making outcomes (Sena et al., 2020). In response, Environmental, Social, and Governance (ESG) factors are being increasingly incorporated into financial systems, adapting decision-making processes to enhance sustainability (Ziolo et al., 2019); (Aldowaish et al., 2022).

As businesses transition toward a circular economy, many are adopting environmental accounting practices that integrate environmental capabilities into their operations, potentially improving both environmental and financial performance (Scarpellini et al., 2020). However, economic considerations typically dominate decision-making processes, often overshadowing critical environmental impacts (Sena et al., 2020). External stakeholder pressure, particularly from consumers and regulatory bodies, has emerged as a crucial driver for sustainable practice adoption, influencing how businesses integrate environmental considerations into their strategies (Iliopoulou et al., 2024). Additionally, the growing need to manage financial risks associated with environmental impacts has led companies to develop integrated models that consider both economic and environmental performance metrics (da Silva et al., 2019).

Despite these various integration methods and drivers, from monetary valuation to ESG integration and environmental accounting, the dominance of economic considerations highlights the need for more standardised and comprehensive approaches to ensure adequate consideration of environmental impacts in decision-making processes.

3.3. Implementation Drivers and Benefits

The implementation of chemical traceability systems in the textile industry is driven by three interconnected forces: regulatory compliance, market competitiveness, and sustainable chemical management, each offering distinct benefits while contributing to the industry's broader sustainability goals.

Regulatory compliance emerges as a primary driver, with expanding legal frameworks creating increasingly stringent requirements. (Schenten et al., 2019) emphasise how these regulations, including the EU's REACH and ESPR, compel companies to adopt comprehensive chemical traceability systems. These systems help organisations identify and substitute hazardous substances, ensuring alignment with both legal requirements and internal company policies (Roos et al., 2020).

Market expectations serve as another crucial driver, reflecting growing societal demands for transparency and sustainability in textile production. (Schenten et al., 2019) highlight how this market pressure creates competitive advantages for brands that demonstrate effective chemical traceability, often encouraging companies to exceed minimum regulatory requirements. By adopting these systems, companies can differentiate themselves in the market while responding to consumer demands for sustainable and transparent products.

The pursuit of green and sustainable chemistry opportunities represents the third key driver, particularly as awareness of chemical risks continues to grow. Traceability systems facilitate the management and substitution of hazardous chemicals throughout the supply chain, addressing the challenges posed by complex and often non-transparent supply networks (Roos et al., 2020). This capability delivers multiple benefits, including enhanced communication and knowledge sharing across the supply chain, improved risk management of hazardous substances, and better sustainability performance (Garcia-Torres et al., 2019).

The implementation of these systems generates significant benefits across multiple dimensions. They provide a platform for communication and knowledge sharing crucial for effective chemicals life cycle management (Roos et al., 2020), while enabling better risk management through full substance traceability (Garcia-Torres et al., 2019). Notably, traceability for sustainability (TfS) integrates governance, collaboration, and tracking mechanisms, contributing to improved triple-bottom-line performance addressing economic, environmental, and social impacts across supply chain actors (Garcia-Torres et al., 2019). These benefits collectively support the textile industry's transition toward more sustainable practices while meeting regulatory requirements and enhancing market competitiveness.

3.4. Implementation Barriers and Challenges

Despite these drivers, significant barriers impede widespread traceability adoption. Supply chain volatility presents a fundamental challenge, with (Schenten et al., 2019) describing how complex and price-driven supply chains complicate consistent traceability implementation.

Policy shortcomings create additional barriers. (Wiesmeth and Häckl, 2015) identify how current environmental policies often lack necessary elements to support traceability initiatives, including insufficient incentives for adopting design-for-environment practices and managing hazardous chemicals effectively.

Resource constraints particularly impact smaller enterprises. The (Doyle et al., 2024) report outlines how SMEs often lack the technical capacity and financial resources needed for comprehensive chemical management systems, creating an implementation gap between large and small industry players.

The barriers to chemical traceability extend beyond technical challenges, revealing a deeper issue of organisational and cultural mindset limitations. These include an entrenched habituation to traditional chemical management approaches focused on restricted substance lists and declarations, a conservative bias toward familiar tools like MS Excel for managing SVHCs, and a prevalent misconception that Digital Product Passports alone ensure chemical traceability. This resistance to change is further compounded by a status quo bias and a focus on short-term roll-out costs while neglecting mid-term benefits. Despite available technological solutions like Full Material Declaration (FMD) systems, as demonstrated by IMDS in the automotive sector, the lack of awareness about the importance of cooperation and supplier engagement continues to impede progress toward comprehensive chemical traceability.

3.5. Implications for Traceability Development

In essence, this analysis reveals several key implications for improving chemical traceability in the textile industry. First, successful implementation requires addressing both economic and institutional factors simultaneously. As Schenten et al., (2019) argue, traceability serves as a driver for more sustainable chemistry, but achieving this requires coordinated action across multiple dimensions.

Policy frameworks must be strengthened to support traceability initiatives. (Wiesmeth and Häckl, 2015) emphasise the need for integrated environmental policies to overcome current implementation challenges. This includes developing stronger enforcement mechanisms and clearer incentives for sustainable practices.

Market mechanisms need better alignment with sustainability goals. This might involve creating stronger economic incentives for traceability adoption while addressing the challenges of volatile supply chains identified by Schenten et al., (2019). Success requires coordinated action to address both incentives and impediments across economic, social, and institutional dimensions.

The path forward requires sustained commitment to addressing both structural and operational challenges. This includes developing harmonised policy frameworks, aligning economic incentives, and building institutional capacity for effective chemical management throughout the textile supply chain. Only through such comprehensive approaches can the industry achieve the level of chemical traceability needed to ensure both human and environmental safety throughout the entire product lifecycle.

4. The Role of System Mapping in Chemical Traceability Implementation

4.1. Aligning Chemical Traceability with EU Sustainability Goals

Following Donella Meadows' definition of a system as an interconnected set of elements that is coherently organized in a way that achieves something as described in the (Meadows, 2009) article, the system maps for textiles and carpets represent two distinct but related visualisations showing how each industry's elements - including their respective chemical traceability systems - are interconnected and organized to achieve chemical traceability, which is why we refer to both "chemical traceability systems" and industry-specific "system maps".

As mentioned previously, chemical traceability in textiles and carpets represents a complex challenge where regulatory requirements, supply chain management, and sustainability goals converge. The textile manufacturing process encompasses multiple stages with distinct chemical inputs: spinning (using auxiliaries and finishing agents), dyeing and printing (requiring textile auxiliaries, dyes, and pigments), and finishing (involving various finishing assistants and technical auxiliaries). Furthermore, many textile companies now specialise in manufacturing products using recycled materials, including plastic. As the European Union introduces new mandates through the Ecodesign for Sustainable Products Regulation (ESPR) and the Digital Product Passport (DPP), the need to track and manage chemicals throughout the value chain becomes increasingly critical. This chapter examines how these requirements intersect with market dynamics and value chain operations to evaluate industry progress toward comprehensive traceability implementation.

The European Union's regulatory landscape will undergo significant changes in 2025-2027, introducing chemical traceability requirements as a key mechanism to enhance transparency and environmental accountability. These regulatory changes align with the EU Green Deal and Sustainable Products Initiative, which support circularity and traceability to achieve sustainability goals (Khan et al., 2021). Core regulations like REACH, CLP (Classification, Labelling and Packaging), and POPs (Persistent Organic Pollutants) establish fundamental requirements for chemical safety and information sharing. These are now being supplemented by the ESPR, which entered into force in July 2024, with specific requirements for textile products expected through delegated acts in early 2026. This regulatory evolution reflects the EU's broader commitment to circularity and environmental protection under the EU Textile Strategy, that defines the ambition and the Green Deal framework. However, implementation faces significant challenges due to the global nature of textile supply chains, where production often occurs in regions with different regulatory standards and enforcement mechanisms.

The complexity of chemical traceability is further amplified by the interaction between different regulatory frameworks and production processes. For both natural fibers like cotton and synthetic materials like polyester, production involves multiple stages where chemicals are introduced - from raw material and recycled material processing through spinning, fabric production, and garment manufacturing. Each stage introduces specific chemical management requirements under various regulations. For instance, while REACH governs general chemical safety, the ESPR and Digital Product Passport will add new layers of traceability requirements. Organisations must therefore develop systems that can track chemicals through complex production and recycling processes while meeting multiple regulatory obligations and adapting to evolving standards.

4.2. The Value Chain Dynamics

The textile and carpet value chains are characterised by fragmentation, with multiple stakeholders, including raw and recycled material suppliers, manufacturers, distributors, and recyclers. This fragmentation exacerbates the challenge of chemical traceability. Industry 4.0 technologies, particularly blockchain and IoT, offer promising solutions for real-time data sharing across stakeholders in chemical traceability (Khan et al., 2021). However, these technologies face significant implementation challenges, including the complexity of integrating diverse systems across dispersed manufacturing networks and the need for clear objectives and appropriate data granularity throughout the supply chain (Ahmed, 2021).

In textiles, institutional incentives, such as those observed in the Dutch circular textile industry, play a pivotal role in transitioning toward a circular economy. (Fischer and Pascucci, 2017) highlight that enabling policies and financial mechanisms can catalyse material recovery and traceability initiatives. Similarly, in the carpet industry, the push for chemical transparency aligns with corporate sustainability strategies and consumer demand for safe and environmentally responsible products. However, resistance to adopting systemic innovations persists, particularly among stakeholders prioritising short-term economic gains over long-term sustainability.

These value chain dynamics and their associated challenges can be better understood through a system map analysis, which visualises the complex interplay between stakeholders, processes, and challenges in both industries.

4.3. System Map Analysis

Mapping the chemical traceability systems for textiles and carpets reveals a complex interplay of stakeholders, processes, and challenges, reflecting the current state of both industries' commitment to transparency and sustainability. A system map provides a visual framework for understanding the connections and dependencies within the value chain, identifying gaps, and uncovering leverage points for systemic improvement.

4.3.1. Textiles: Fragmented Accountability and Emerging Solutions

The textile industry's system map highlights various stages spanning raw and recycled material sourcing, production, distribution, use, and end-of-life processes. This structure creates several challenges for chemical traceability:

<u>1. Lack of Uniform Standards:</u> Different regions and organisations follow varying regulatory and operational standards for chemical management, which complicates traceability efforts. Companies operating internationally face additional difficulties in aligning their practices with inconsistent global frameworks (Fischer and Pascucci, 2017).

2. Technological Integration Gaps: While Industry 4.0 technologies are being adopted to enhance traceability, these solutions are not yet uniformly implemented across the value chain (Khan et al., 2021). Smaller suppliers, especially in developing economies (mostly in the Global South), often lack the technical infrastructure or resources to integrate such systems. Several EU-funded initiatives focus on supporting SMEs in adopting traceability technologies, providing financial assistance, resources, and collaborative opportunities to drive innovation and sustainability. Notable examples include the TRACE4EU project, part of the Digital Europe Programme, which leverages blockchains to enhance document traceability and expand the European Blockchain Services Infrastructure. The STEP Scale Up scheme, under the European Innovation Council (EIC), provides substantial funding to scale innovations in strategic sectors, including traceability. The European Union supports SME digitalisation through complementary programs. The Digital Europe Programme leads this effort by providing comprehensive support through funding mechanisms, Digital Innovation Hubs, skill development initiatives, transformation projects, sustainability-focused solutions, and collaborative networks. This enables businesses to adopt advanced technologies while addressing key barriers such as costs, expertise gaps, and infrastructure limitations. Complementing these efforts, the COSME Programme specifically focuses on facilitating SMEs' access to finance for technology integration, creating a robust support ecosystem for digital transformation. Finally, the Horizon Europe Programme, the EU's flagship research and innovation initiative, enables SMEs to participate in collaborative projects aimed at advancing traceability technologies. These programmes aim to collectively empower SMEs to improve transparency, efficiency, and sustainability in their operations.

3. Consumer Pressure: Growing consumer demand for transparency and sustainable products is driving innovation in chemical traceability within the textile industry, notably through Digital Product Passports that detail chemical composition and environmental impacts (Schenten et al., 2019) (Calderon-Monge et al., 2020) (Calderon-Monge et al., 2020) (Ospital et al., 2023). While larger textile companies lead these efforts through comprehensive traceability measures and digital tools due to their superior resources and supply chain management capabilities (Garcia-Torres et al., 2022) (Plakantonaki et al., 2023); (Alves et al., 2023), smaller enterprises struggle to adopt similar innovations due to limited resources and expertise, often falling behind in implementing these costly and complex traceability systems (Harsanto et al., 2023) (Luján-Ornelas et al., 2020).

Despite these challenges, system maps for textiles reveal significant opportunities for improvement. Enhanced collaboration between textile manufacturers, their suppliers, recyclers, and technology providers can facilitate data sharing and drive circularity within the industry.

While direct harmonisation of international chemical regulations remains complex due to varying legislative systems, REACH and the EU Green Deal can serve as model frameworks for developing chemical traceability approaches in other regions. These EU frameworks provide valuable principles and practices that other jurisdictions might adapt according to their specific contexts. This could contribute to the development of more consistent chemical traceability practices globally, while emphasising the critical need for a harmonised digital transparency and traceability system that enables informed decision-making across all life stages of materials and products for regulatory agencies, companies, and consumers - a fundamental requirement for achieving a circular economy free from harmful chemicals (HEJSupport, n.d.)

4.3.2. Carpets: Closed-Loop Potential and Persistent Barriers

The carpet industry presents a slightly different picture, with a more defined end-of-life process due to established recycling practices in some regions. The system map for carpets showcases several distinct characteristics:

1. End-of-Life Recycling Systems: Unlike textiles, carpets usually have a longer lifespan and are more likely to enter structured recycling streams. However, this potential for closed-loop systems faces significant challenges due to the presence of harmful chemicals in carpets, including flame retardants (PBDEs), phthalates, heavy metals, and PFAS. These substances can persist through the recycling process and remain in the recycled materials, creating risks for human health and the environment. The lack of transparency and information about chemical content in carpets further complicates recycling efforts, particularly when the recycled materials are repurposed into products like insulation or padding. Despite these challenges, the carpet industry presents opportunities for material recovery and reuse within closed-loop systems (Fischer and Pascucci, 2017).

2. Corporate Sustainability Initiatives: Larger carpet manufacturers are embedding chemical traceability into their broader ESG (Environmental, Social, and Governance) strategies, using it as a tool to gain consumer trust and meet regulatory requirements. These initiatives involve proprietary recycling technologies that allow for the recovery of valuable materials such as nylon. (Spadea et al., 2015)

3. Barriers for SMEs: Similar to the textile sector, small and medium enterprises (SMEs) in the carpet industry face significant barriers to adopting chemical traceability systems, including cost constraints and limited access to technology.

On a positive note, the carpet industry has established traceability solutions, particularly for European manufacturers. The GUT-PRODIS system, developed in 2007 from the original GUT label, provides a comprehensive traceability framework through its three-pillar approach: chemical testing through the GUT system, standardized FCSS symbols for performance characteristics, and unique product identification via ID numbers and QR codes. Since 2020, this system has evolved into a complete Product Passport accessible online, demonstrating the industry's capability to implement sophisticated traceability solutions. However, challenges remain in achieving comprehensive chemical traceability across the carpet market. While European producers have access to the GUT-PRODIS system through ECRA, not all carpet products in the European market are covered by this traceability scheme. Some carpet products, particularly imports, may lack equivalent transparent chemical information.

The key opportunity for advancing chemical traceability lies in establishing a globally harmonized digital transparency and traceability system for all manufactured materials and products. This comprehensive approach should incorporate digital product passports and a global database accessible to all value chain stakeholders. While existing systems like GUT-PRODIS provide a foundation, the focus should shift from regional solutions - like European Union market coverage - to implementing consistent chemical traceability standards worldwide. This global system would enable better tracking and management of chemical content across product lifecycles and international markets, (HEJSupport, n.d.), https://www.globalchemicaltransparency.org/; https://www.globalchemicaltransparency.org/#a13lightbox-work-12609; last access 3/02/2025.

As advanced by (Kiekens et al., 2022), a system map serves as a visual representation of complex adaptive systems, illustrating causal relationships and interconnections between various elements to reveal emergent patterns and self-organising dynamics. This analytical tool enables researchers and policymakers to develop a holistic, multi-perspective understanding of complex issues, identify root causes, uncover feedback loops, and pinpoint strategic intervention points while incorporating principles of systems thinking and trans disciplinarity.

The system map analysis highlights key opportunities for advancing chemical traceability in the carpet industry, including cross-industry learning and innovative business models. By leveraging best practices from other sectors, such as automotive and packaging, scalable solutions for chemical traceability can be developed and adapted to industry needs. Additionally, exploring business models like product-as-a-service, where carpets are leased instead of sold, offers a promising approach to ensuring their return to manufacturers for proper recycling and chemical accountability.

4.3.3. Comparative Analysis of the System Maps

A comparative analysis of the system maps for textiles and carpets highlights several shared systemic challenges. While the carpet industry has established the GUT-PRODIS system for chemical traceability, data gaps still exist, particularly regarding products not covered by this system and in the interoperability of data between different traceability frameworks. These gaps can impede the achievement of seamless chemical traceability across the entire market. Additionally, disparities in resources and technical expertise among stakeholders, particularly small and medium enterprises (SMEs), create bottlenecks that slow progress. Regulatory misalignment further aggregates to these difficulties, with variations in local, regional, and global policies adding complexity and blocking the development of cohesive chemical traceability systems.

The parallel challenges faced by both textile and carpet industries reveal important patterns in traceability implementation. These shared dynamics aggregate standards, technology integration, regulatory alignment, consumer demands, and specific constraints faced by SMEs, while also highlighting the distinct characteristics of each sector.

Despite these challenges, there are notable opportunities for advancement in both sectors. Standardisation across industries can bridge existing gaps and streamline traceability practices, fostering greater consistency and efficiency. Furthermore, digital tools present scalable solutions for managing data and enhancing transparency including its availability to the public and regulators, especially in the global south. Leveraging these technologies, a constructive mindset and aligning stakeholders around shared goals can act as catalysts for progress, enabling both industries to overcome barriers and make significant strides toward sustainable and accountable practices.

The system maps for textiles and carpets illustrate a transitional state where some stakeholders are leading efforts toward value creation and ecosystem development, while others remain rooted in status quo maintenance. The ability to achieve meaningful progress in chemical traceability lies in addressing systemic challenges, including setting up a cross-sectoral globally harmonised transparency and traceability system, fostering cross-sector collaboration, and scaling technological solutions. By leveraging the insights provided by these system maps, stakeholders can identify leverage points and implement targeted interventions to drive systemic change, ensuring both industries align with sustainability and circular economy objectives.

4.4. Key Leverage Points

Building upon Donella Meadows' influential framework of leverage points (Meadows, 1999), which offers a systematic approach to understanding how and where to intervene in complex systems, this analysis provides a tailored adaptation for chemical traceability in the textile industry, enriching our understanding of potential intervention points for transformative change. This fundamental work identifies twelve points where one can intervene in a complex system, arranged in ascending order of their power to create change. These points of intervention range from straightforward adjustments like parameters and numbers (least effective) to the profound challenge of transcending existing paradigms (most powerful). Drawing from decades of systems thinking research, this framework offers practical guidance for achieving maximum impact when intervening in complex systems.

In the context of chemical traceability in the textile industry, these leverage points take on particular significance. At the most basic level (points 12-9), we find technical interventions like chemical threshold limits, testing quantities, buffer stocks of compliant materials, and information flow delays. While these are the most commonly targeted areas for intervention, they often produce limited results in isolation. The middle-tier leverage points (8-5) address more structural elements: feedback loops like market responses to violations, information flows increased through data sharing platforms, and the rules governing chemical management. These interventions tend to have more substantial impacts because they affect how the system operates rather than just its parameters.

The highest-impact leverage points (4-1) deal with the system's fundamental characteristics: its ability to self-organise and innovate, its goals - such as achieving full chemical transparency, and its underlying paradigms. The current paradigm shift from information asymmetry to transparency, driven by growing societal awareness of chemical impacts on health and the environment, represents a powerful leverage point. This shift is further amplified by technological evolution and increasing reputational risks for the textile industry. The ultimate leverage point lies in transcending existing paradigms altogether – recognising that our understanding of chemical safety and management is evolving and requires flexible, adaptive approaches.

The textile sector is facing unprecedented pressure to transform its approach to chemical management, driven by consumer awareness, scientific evidence, regulatory requirements, and technological capabilities. By understanding these leverage points, stakeholders can focus their efforts on interventions that will create lasting, systemic change rather than temporary fixes. For instance, while implementing stricter testing parameters (a low-leverage intervention) might provide some immediate benefits, developing industry-wide transparency platforms and shifting the fundamental business paradigm toward chemical safety as a competitive advantage (high-leverage intervention point) will likely create a sustainable and impactful level-playing field.

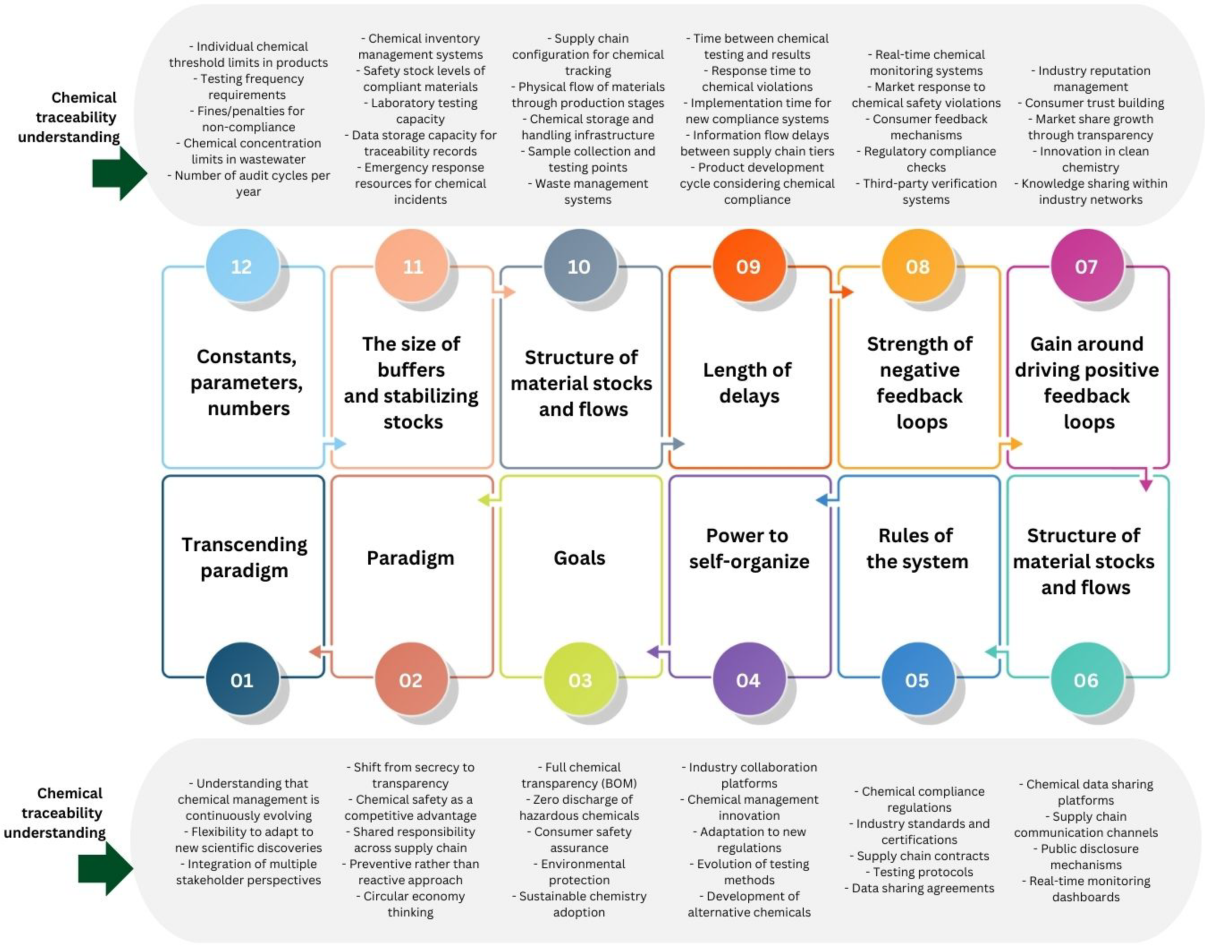

Figure 5: Key leverage points in the context of chemical traceability in the textile industry.

The framework suggests that successful chemical traceability initiatives must operate at multiple levels simultaneously, with particular emphasis on the higher-leverage points. This means not only implementing technical solutions but also fostering industry collaboration, building new information-sharing infrastructures, and fundamentally rethinking the relationship between chemical management, business progress, and societal well-being.

4.5. Framing the Status Quo

The framing of chemical traceability in textiles and carpets can be analysed across three distinct paradigms: status quo maintenance, value creation, and ecosystem development, as outlined by (Gunderson et al., 2020). Many stakeholders currently approach chemical traceability as a compliance-driven exercise, primarily focused on meeting minimum national regulatory requirements. This narrow focus often prevents broader systemic changes and limits the potential for innovation within the industry.

In contrast, some larger industry players are leveraging chemical traceability as a tool for value creation. By integrating traceability into their product offerings, these companies differentiate themselves in the market, appealing to environmentally conscious consumers and embedding sustainability into their value propositions. This strategy meets various national and regional compliance standards and encourages setting up parallel industry-driven transparency and traceability standards, potentially with different priority chemicals and disclosure thresholds, and also positions these businesses as leaders in sustainability-driven innovation.

However, SMEs might find it difficult to compete with these established players, especially if they cannot meet the same level of transparency and traceability. They often struggle to keep up with the constantly evolving regulatory landscape and new standards developed by bigger industry players. This can result in non-compliance risks and potential penalties. Thus, a globally harmonised transparency and traceability system reduces the complexity of adhering to multiple national, regional and industry standards. This makes it easier for SMEs to comply with regulations without needing extensive resources. A harmonised system can simplify internal processes, making it easier for SMEs to track and report their sustainability efforts. This can lead to better decision-making and more efficient operations as well as level the playing field and facilitate international trade.

Ecosystem development, while still in its early stages, is emerging in specific cases where cross-sector collaboration fosters innovation and systemic change. Partnerships between the textile and recycling industries, for example, are demonstrating the potential for transformative shifts that extend beyond individual companies or sectors. These collaborative frameworks enable the sharing of resources, knowledge, and technologies, paving the way for a more integrated and sustainable value chain.

In sum, the current trajectory of chemical traceability for the textile industry reflects a mixed landscape. Status quo maintenance continues to dominate in less-regulated regions, while value creation is more prevalent among industry leaders. Signs of ecosystem development are evident but remain nascent. To accelerate progress, it is essential to develop a cross-sectoral globally harmonised transparency and traceability system, implement targeted policy incentives, encourage technological adoption, and align stakeholder efforts. These measures can create a level playing field, enhance resilience, and promote sustainability across the value chain, ultimately driving meaningful systemic transformation.

5. Recommendations for Training Scheme Development

The implementation of chemical traceability in textile value chains requires a nuanced and multi-layered training approach. Based on the analyses conducted previously, this chapter provides detailed recommendations for developing effective training schemes that address the diverse needs of stakeholders while ensuring consistent messaging about traceability objectives.

5.1. Target Participants

The selection of training participants should follow three fundamental criteria that ensure meaningful engagement and practical implementation of traceability concepts. First, participants should represent organisations directly involved in chemical or material flows within textile value chains, as these stakeholders will be responsible for implementing chemical traceability systems. Second, they should hold positions that enable them to influence decision-making processes within their organisations, ensuring that training insights can be translated into actionable changes. Third, while participants with varying levels of experience in chemical management systems are welcome, basic introductory materials will be provided before the training to ensure all stakeholders, including SMEs and smaller retailers, can effectively engage with traceability concepts. This approach ensures that both newcomers and experienced organisations can participate meaningfully in the training, reflecting the diverse maturity levels present in the textile industry.

For optimal results, training groups should include representatives from four key stakeholder categories: industry professionals who manage chemical processes and supply chains, recyclers, policy stakeholders who shape and enforce regulations, technical experts who implement chemical traceability systems, and support organisations that facilitate industry transformation, including civil society organisations, trade unions and consumer groups, as well as rightsholders. This diverse composition creates valuable opportunities for cross-sectoral learning and collaboration.

5.2. Training Formats

The complexity of chemical traceability demands a variety of training formats that build upon each other to create a comprehensive learning journey. At the foundation level, interactive workshops serve as the primary vehicle for engagement. These workshops could employ the World Café methodology, which has proven particularly effective. This format enables participants to rotate through different stations, each focusing on a specific aspect of traceability such as regulatory requirements, technical implementation, supply chain coordination or public access to information.

Case study-based learning provides practical context and real-world application, building upon this foundation. These case studies should be drawn from successful implementations within the textile industry, focusing on different scales of operation from large manufacturers to small-medium enterprises. Each case study should include not only successes but also challenges encountered and solutions developed, offering valuable learning opportunities from actual implementation experiences.

Simulation games and case studies represent the next level of engagement, offering participants the opportunity to experience traceability implementation in a risk-free environment. These simulations should model real-world scenarios such as supply chain disruptions, new regulatory requirements, or stakeholder negotiations. Through role-playing exercises, participants can develop practical skills in managing chemical traceability systems while understanding the perspectives of different stakeholders.

Within these various training formats, the specific design of workshops requires particular attention to create effective learning environments.

5.2.1. Workshop Design

The design of training workshops should prioritise creating an environment where participants feel both understood and empowered to co-create. This can be achieved through a three-tier approach to the workshop structure. The first tier focuses on establishing common ground by acknowledging the specific challenges and constraints faced by different stakeholder groups. For instance, manufacturers might be concerned about protecting confidential business information, while regulators need to ensure comprehensive compliance monitoring and the safety of human health and the environment, and consumers and recyclers require access to information for making informed decisions. Understanding these perspectives helps create a foundation of mutual respect and practical problem-solving.

The second tier introduces collaborative learning methods, such as the World Café format demonstrated in a policy workshop conducted by the ECHT project. This approach allows participants to engage with different aspects of traceability implementation while building on each other's insights. Small group rotations ensure that participants can deeply explore specific topics while benefiting from diverse perspectives.

The third tier emphasises practical application through simulation exercises and real-world case studies. These hands-on elements help participants understand how traceability concepts apply to their specific contexts while building confidence in implementing new systems and processes. Digital tools, including AI-supported learning platforms, can enhance these practical exercises by providing immediate feedback and personalised guidance.

5.3. Audience-Specific Tailoring

For industry professionals, the training programme should emphasise practical implementation strategies and business value creation. These participants need detailed understanding of cost-benefit analysis methodologies specific to their operational scale, technical requirements for different types of textile products and processes, integration strategies for existing quality management systems, data management protocols that protect confidential business information, risk assessment and mitigation strategies for traceability implementation.

Policy aspects present in the training for the textile industry should concentrate on sharing effective regulatory frameworks and uptake of enforcement mechanisms. Key areas include international standards harmonization and alignment strategies, development of evidence-based reporting, impact assessment methodologies for different regulatory approaches, cross-border cooperation frameworks for traceability enforcement, and balance between transparency requirements and business confidentiality.

Technical training should dive deep into implementation methodologies and quality assurance across multiple critical dimensions. Essential components cover data architecture design for chemical traceability systems, including substance identification and tracking mechanisms, hazard assessment protocols, and risk management frameworks. The training should integrate protocols for different technology platforms, quality control mechanisms for traceability data, regulatory compliance monitoring systems, and methodologies for addressing common implementation challenges. Special emphasis should be placed on establishing robust information sharing protocols across the supply chain to ensure seamless data flow and effective chemical management.

Training for support organisations should focus on facilitation and bridge-building roles. Key elements incorporate stakeholder engagement strategies across the value chain, communication techniques for different audience types, partnership building methodologies, impact measurement and reporting frameworks, and resource mobilisation strategies for traceability initiatives.

On another layer, the mindsets approach reframes how we understand and address the overarching sustainability challenges (Wamsler et al., 2020). Rather than viewing sustainability through a single lens, this approach recognizes different cognitive frameworks that shape how decision-makers evaluate and respond to environmental issues (Meath et al., 2024). These frameworks operate on multiple levels. At the operational level, leaders focus on immediate, practical solutions, while at the societal level, they consider broader social and environmental impacts (Benkert, 2021). Research shows that individuals often shift between these perspectives depending on context and circumstances (Schulte and Paris, 2024). Effective sustainability leadership requires integrating environmental, social, and economic considerations while moving beyond pure economic returns (Fry and Egel, 2021). This integrated approach helps organisations recognize and manage the inherent tensions in sustainability efforts, enabling more effective climate action through improved communication and collaboration across stakeholder groups (Wamsler et al., 2020).

This perspective could facilitate to understand how different industrial organisations approach and engage with chemical traceability in their operations and supply chains. This analytical framework moves beyond traditional segmentation approaches, recognizing that organisations' attitudes toward chemical traceability are not fixed but rather exist on a spectrum that can shift based on context, experience, and external pressures. The analysis particularly focuses on how organisations perceive, implement, and respond to chemical traceability initiatives, offering insights into both barriers and opportunities for advancing responsible chemical management.

Methodologically, the analysis builds upon established customer mindset research in sustainability, translating consumer-focused insights into an industrial context. The framework identifies four distinct mindsets - Unaware, Apathetic, Skeptical, and Engaged - each characterized by specific attitudes, behaviors, and response patterns to chemical traceability initiatives. These mindsets are mapped along two key dimensions: level of awareness / information and degree of active engagement with chemical traceability practices. This approach allows for a more nuanced understanding of how organisations can move from one mindset to another and what interventions might be most effective at each stage.

The findings reveal that organisational mindsets toward chemical traceability are more fluid and context-dependent than previously understood. Rather than treating chemical traceability as a purely technical or compliance challenge, the analysis shows that psychological and organisational factors play crucial roles in determining engagement levels. Each mindset presents unique barriers and opportunities for advancement, requiring tailored approaches for activation. The analysis particularly highlights the importance of addressing emotional and practical barriers in the Unaware and Apathetic mindsets, building trust and providing concrete evidence for the Skeptical mindset, and maintaining momentum and providing scalable solutions for the Engaged mindset. These insights provide a foundation for developing more effective strategies using behavioral economics to advance chemical traceability across industries.

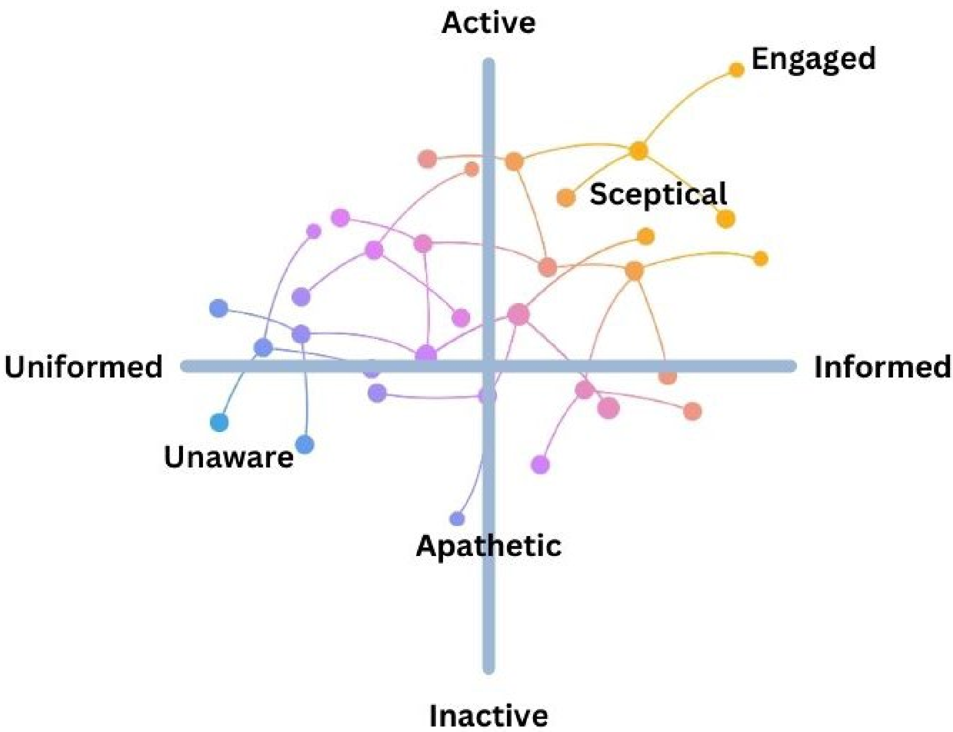

Figure 6: Mindsets representation

Beyond content customisation, the success of training programmes depends critically on choosing optimal delivery methods that resonate with each audience segment.

5.4. Delivery Methods

The delivery of training content should employ a blended learning approach that maximises engagement and knowledge retention while accommodating different learning styles and operational constraints.

Face-to-face training remains essential for building relationships and developing practical skills. These sessions should include hands-on workshops with physical examples of traceability implementation, expert-led discussions of complex scenarios, peer learning opportunities through structured networking, practical exercises using actual traceability tools and systems, and site visits to organisations with successful traceability implementations.

Digital platforms extend the reach and accessibility of training while providing opportunities for continuous learning. These platforms should incorporate interactive e-learning modules for foundational concepts, virtual reality simulations of supply chain scenarios, online collaboration tools for group projects, digital resource libraries with updated materials, and AI-powered learning assistance for personalised support.

The training programme should establish pathways for ongoing learning and development through continuous professional development. This includes regular update sessions on new technologies and regulations, mentoring programmes pairing experienced implementers with newcomers, communities of practice for peer support and knowledge sharing, professional certification programmes for traceability expertise, and regular assessments to identify emerging training needs.

Implementation support plays a crucial role in training effectiveness. This includes helpdesk services for implementation questions, technical assistance programmes for specific challenges, regular feedback sessions to identify improvement areas, success story documentation and sharing, and adaptation support for different organisational contexts.

Through this comprehensive approach to training development and delivery, stakeholders can build the capabilities needed to implement effective chemical traceability systems across textile value chains. The success of these training programmes should be measured not only through participant satisfaction but also through practical implementation outcomes in their respective organisations. Regular evaluation and updating of training materials ensure continued relevance and effectiveness in supporting the broader goal of achieving comprehensive traceability by 2027.

6. Towards a Sustainable Chemical Traceability Framework

The analysis of chemical traceability in the textile and carpet sectors reveals a complex landscape where regulatory demands, market pressures, and technological capabilities intersect. Through examining the current state, several key findings and insights emerge that articulate the path forward for implementing effective chemical traceability systems.

The interconnected nature of chemical traceability challenges becomes apparent when considering the interdependencies between various stakeholders. Supply chain actors, from raw and recycled material suppliers to end-product manufacturers and waste operators, must coordinate their efforts while navigating different regulatory frameworks and market expectations. This interdependence extends beyond individual companies to cover entire industrial ecosystems, where the actions of one participant can significantly impact others' ability to implement effective chemical traceability systems.

When framing the status quo, we observe a spectrum of approaches ranging from basic compliance to innovative value creation. Many organisations, particularly SMEs, remain focused on meeting minimum regulatory requirements, while industry leaders are leveraging traceability as a competitive advantage, including developing various parallel transparency and traceability standards, potentially with different priority chemicals and disclosure thresholds. This disparity highlights the need for a comprehensive globally harmonised transparency and traceability system that can help all industry participants transition toward more advanced chemical traceability systems.

Creating a level playing field emerges as a critical concern for successful implementation. The current landscape shows significant disparities in resources, technical capabilities, and market access between large corporations and SMEs. These differences risk creating a two-tier system where only well-resourced organisations can fully implement traceability measures. Addressing this imbalance requires targeted support mechanisms, including accessible training programmes and technical assistance, particularly for SMEs.

The resilience of chemical traceability systems proves essential for long-term success. Organisations must develop capabilities to maintain traceability practices despite supply chain disruptions, changing regulatory requirements, and evolving market demands. This resilience depends on robust technical systems and also on organisational capacity building and strong collaborative networks.

Sustainability considerations are integrated into every aspect of chemical traceability implementation. Beyond environmental protection, sustainable approaches must account for economic viability and social responsibility. This triple bottom line perspective helps ensure that chemical traceability systems contribute to broader sustainability goals while remaining practically achievable for the industry and value chain.

The key findings from our analysis converge around five fundamental dimensions that shape successful traceability implementation. These dimensions, synthesised in Figure 7, involve systemic approach, capacity building, technology adoption, policy frameworks, and market dynamics.

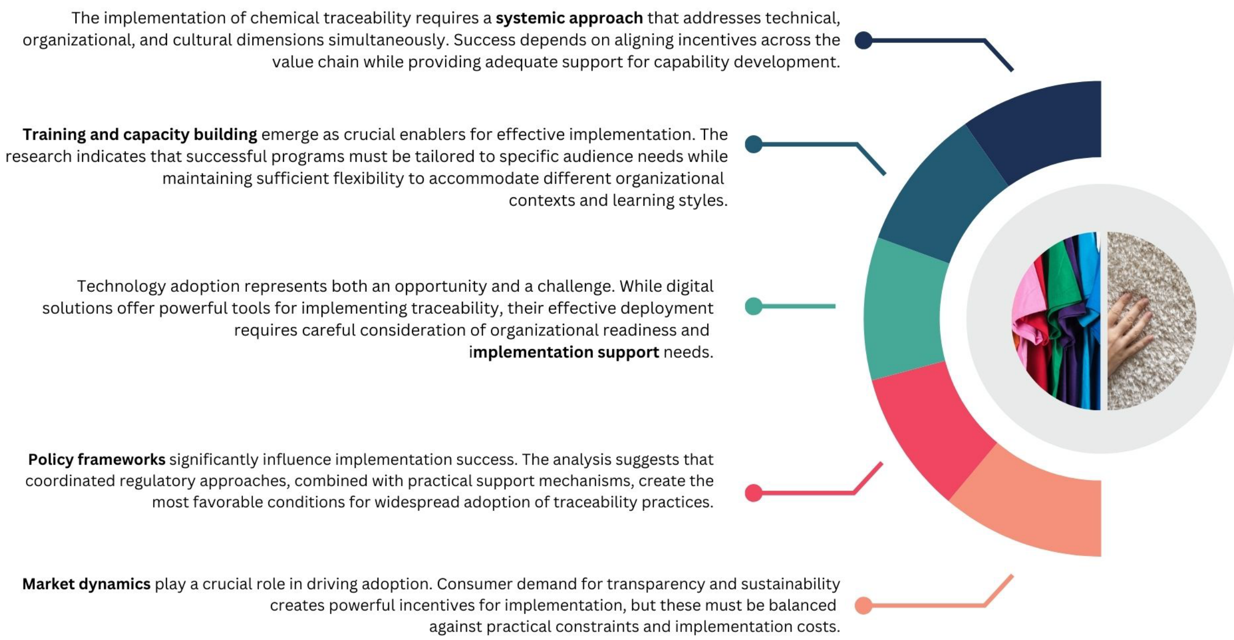

Figure 7: Synthesis of key findings and insights from the status quo analysis.

These findings emphasise the importance of developing a comprehensive cross-sectoral globally harmonised system that can help organisations navigate the complexities of chemical transparency and traceability implementation. The path forward requires sustained commitment to addressing both structural and operational challenges while maintaining focus on long-term sustainability goals.

As the textile and carpet industries continue their transformation toward greater transparency and sustainability, chemical traceability will play an increasingly central role. Achievement in this transformation depends on creating systems that are technically robust, economically viable, and socially responsible. By addressing the challenges and opportunities identified in this analysis, stakeholders can work together to build more sustainable and transparent value chains that benefit all participants while protecting human health and the environment.

The journey toward comprehensive chemical traceability represents a significant challenge, but also an opportunity for meaningful industry transformation. Through coordinated action, sustained commitment, and appropriate support structures, the textile and carpet sectors can achieve the level of transparency and sustainability demanded by evolving markets and regulatory frameworks.

REFERENCES

Ahmed, W.; M.B., 2021. Blockchain-Enabled Supply Chain Traceability in the Textile and Apparel Supply Chain: A Case Study of the Fiber Producer, Lenzing.

Aldowaish, A., Kokuryo, J., Almazyad, O., Goi, H.C., 2022. Environmental, Social, and Governance Integration into the Business Model: Literature Review and Research Agenda. Sustainability 14, 2959. https://doi.org/10.3390/su14052959

Alves, L., Sá, M., Cruz, E.F., Alves, T., Alves, M., Oliveira, J., Santos, M., Rosado da Cruz, A.M., 2023. A Traceability Platform for Monitoring Environmental and Social Sustainability in the Textile and Clothing Value Chain: Towards a Digital Passport for Textiles and Clothing. Sustainability 16, 82. https://doi.org/10.3390/su16010082

Antal, B., Kuki, Á., Nagy, L., Nagy, T., Zsuga, M., Kéki, S., 2016. Rapid detection of hazardous chemicals in textiles by direct analysis in real-time mass spectrometry (DART-MS). Anal Bioanal Chem 408, 5189–5198. https://doi.org/10.1007/s00216-016-9603-z

Benkert, J., 2021. Reframing Business Sustainability Decision-Making with Value-Focussed Thinking. Journal of Business Ethics 174, 441–456. https://doi.org/10.1007/s10551-020-04611-4

Bertone, M.P., Meessen, B., 2013. Studying the link between institutions and health system performance: a framework and an illustration with the analysis of two performance-based financing schemes in Burundi. Health Policy Plan 28, 847–857. https://doi.org/10.1093/heapol/czs124

Bharati, M.S.S., Soma, V.R., 2021. Flexible SERS substrates for hazardous materials detection: recent advances. Opto-Electronic Advances 4, 210048–210048. https://doi.org/10.29026/oea.2021.210048

Bour, A., Budde Christensen, T., Hunka, A.D., Palmqvist, A., Skjold, E., Syberg, K., 2023. Implications of circular textile policies for the future regulation of hazardous substances in textiles in the European Union. Science of The Total Environment 896, 165153. https://doi.org/10.1016/j.scitotenv.2023.165153

Calderon-Monge, E., Pastor-Sanz, I., Sendra Garcia, F.J., 2020. Analysis of sustainable consumer behavior as a business opportunity. J Bus Res 120, 74–81. https://doi.org/10.1016/j.jbusres.2020.07.039

Camera Nazionale della Moda Italiana, 2021. Le buone prassi di fabbricazione. Linee guida sull'uso dei prodotti chimici nelle filliere produttive della moda.

da Costa Junior, J., Diehl, J.C., Snelders, D., 2019. A framework for a systems design approach to complex societal problems. Design Science 5, e2. https://doi.org/10.1017/dsj.2018.16

da Silva, C., Barbosa-Póvoa, A.P., Carvalho, A., 2019. Green Supply Chain: Integrating Financial Risk Measures while Monetizing Environmental Impacts. pp. 1549–1554. https://doi.org/10.1016/B978-0-12-818634-3.50259-9

Di Bella, L., Katsinis, A., Lagüera-González, J., Odenthal, L., Hell, M., Lozar, B.., 2023. Annual report on European SMEs 2022/2023 : SME performance review 2022/2023. Publications Office of the European Union.

Doyle, H., Flexman, K., Keyte, I., Reynolds, K., Tyers, J., Serrano Valverde, B., Whiting, R., Løfstedt, M., Fogh Mortensen, L., 2024. An assessment on PFAS in textiles in Europe's circular economy.

European Environmental Agency, 2023. EU exports of used textiles in Europe's circular economy. https://doi.org/doi:10.2800/037373

European Environmental Agency, 2019. Emerging chemical risks in Europe — 'PFAS.' https://doi.org/doi:10.2800/486213

Fan, K., Hui, E.C.M., 2020. Evolutionary game theory analysis for understanding the decision-making mechanisms of governments and developers on green building incentives. Build Environ 179, 106972. https://doi.org/10.1016/j.buildenv.2020.106972

Fischer, A., Pascucci, S., 2017. Institutional incentives in circular economy transition: The case of material use in the Dutch textile industry. J Clean Prod 155, 17–32. https://doi.org/10.1016/j.jclepro.2016.12.038

Fry, L. W., Egel, E., 2021. Global Leadership for Sustainability. Sustainability 13, 6360. https://doi.org/10.3390/su13116360

Garcia-Torres, S., Albareda, L., Rey-Garcia, M., Seuring, S., 2019. Traceability for sustainability – literature review and conceptual framework. Supply Chain Management: An International Journal 24, 85–106. https://doi.org/10.1108/SCM-04-2018-0152

Garcia-Torres, S., Rey-Garcia, M., Sáenz, J., Seuring, S., 2022. Traceability and transparency for sustainable fashion-apparel supply chains. Journal of Fashion Marketing and Management: An International Journal 26, 344–364. https://doi.org/10.1108/JFMM-07-2020-0125

Gunderson, R., Stuart, D., Petersen, B., 2020. The fossil fuel industry's framing of carbon capture and storage: Faith in innovation, value instrumentalization, and status quo maintenance. J Clean Prod 252, 119767. https://doi.org/10.1016/j.jclepro.2019.119767

Harsanto, B., Primiana, I., Sarasi, V., Satyakti, Y., 2023. Sustainability Innovation in the Textile Industry: A Systematic Review. Sustainability 15, 1549. https://doi.org/10.3390/su15021549

HEJSupport, SSNC, groundWork SA: Transparency and traceability systems for plastics - Design and practicability considerations, March 2024, https://www.globalchemicaltransparency.org/wp-content/uploads/2024/02/INC4-Transparency-Information-paper.pdf

Ho, H.T.T., Watanabe, T., 2020. The dynamics of textile firm responses to the restriction of endocrine disrupting surfactants: a Vietnam case study. J Risk Res 23, 504–521. https://doi.org/10.1080/13669877.2019.1591490

Hurwicz, L., 1979. Socialism and incentives: Developing a framework. J Comp Econ 3, 207–216. https://doi.org/10.1016/0147-5967(79)90022-2

Hynes, N.R.J., Kumar, J.S., Kamyab, H., Sujana, J.A.J., Al-Khashman, O.A., Kuslu, Y., Ene, A., Suresh Kumar, B., 2020. Modern enabling techniques and adsorbents based dye removal with sustainability concerns in textile industrial sector -A comprehensive review. J Clean Prod 272, 122636. https://doi.org/10.1016/j.jclepro.2020.122636

Iliopoulou, E., Vlachvei, A., Koronaki, E., 2024. Environmental Drivers, Environmental Practices, and Business Performance: A Systematic Literature Review and Future Research Directions. Sustainability 16, 4725. https://doi.org/10.3390/su16114725

Ivy, N., 2021. Essentials of chemical management system for textiles, in: Chemical Management in Textiles and Fashion. Elsevier, pp. 99–112. https://doi.org/10.1016/B978-0-12-820494-8.00005-8

Jönsson, C., Roos, S., Hildenbrand, J., 2021. Chemical management system in textiles, in: Chemical Management in Textiles and Fashion. Elsevier, pp. 1–18. https://doi.org/10.1016/B978-0-12-820494-8.00001-0

Khan, I.S., Ahmad, M.O., Majava, J., 2021. Industry 4.0 and sustainable development: A systematic mapping of triple bottom line, Circular Economy and Sustainable Business Models perspectives. J Clean Prod 297, 126655. https://doi.org/10.1016/j.jclepro.2021.126655

Kiekens, A., Dierckx de Casterlé, B., Vandamme, A.-M., 2022. Qualitative systems mapping for complex public health problems: A practical guide. PLoS One 17, e0264463. https://doi.org/10.1371/journal.pone.0264463

Kumar, L., Kamil, I., Ahmad, M., Naqvi, S.A., Deitch, M.J., Amjad, A.Q., Kumar, A., Basheer, S., Arshad, M., Sassanelli, C., 2022. In-house resource efficiency improvements supplementing the end of pipe treatments in textile SMEs under a circular economy fashion. Front Environ Sci 10. https://doi.org/10.3389/fenvs.2022.1002319

Kwiatkowski, C.F., Andrews, D.Q., Birnbaum, L.S., Bruton, T.A., DeWitt, J.C., Knappe, D.R.U., Maffini, M. V., Miller, M.F., Pelch, K.E., Reade, A., Soehl, A., Trier, X., Venier, M., Wagner, C.C., Wang, Z., Blum, A., 2020. Scientific Basis for Managing PFAS as a Chemical Class. Environ Sci Technol Lett 7, 532–543. https://doi.org/10.1021/acs.estlett.0c00255

Ladaresta, F., Manniello, M.D., Östman, C., Crescenzi, C., Holmbäck, J., Russo, P., 2018. Chemicals from textiles to skin: an in vitro permeation study of benzothiazole. Environmental Science and Pollution Research 25, 24629–24638. https://doi.org/10.1007/s11356-018-2448-6

Luján-Ornelas, C., Güereca, L.P., Franco-García, M.-L., Heldeweg, M., 2020. A Life Cycle Thinking Approach to Analyse Sustainability in the Textile Industry: A Literature Review. Sustainability 12, 10193. https://doi.org/10.3390/su122310193

Meadows, D., 1999. Leverage Points: Places to Intervene in a System - The Donella Meadows Project. Academy for Systems Change. https://donellameadows.org/archives/leverage-points-places-to-intervene-in-a-system/

Meadows, D.H.W.D., 2009. System Thinking: A Primer. Earthscan Publications.

Meath, C., Newey, L., Griffiths, A., 2024. 'I have to put my citizen's hat on': Operational and societal mindsets to provide a new perspective on organisational decision-making for sustainability. Bus Strategy Environ 33, 6652–6670. https://doi.org/10.1002/bse.3836

Nielsen, I.E., Majumder, S., Sana, S.S., Saha, S., 2019. Comparative analysis of government incentives and game structures on single and two-period green supply chain. J Clean Prod 235, 1371–1398. https://doi.org/10.1016/j.jclepro.2019.06.168

Ospital, P., Masson, D., Beler, C., Legardeur, J., 2023. Toward product transparency: communicating traceability information to consumers. International Journal of Fashion Design, Technology and Education 16, 186–197. https://doi.org/10.1080/17543266.2022.2142677

Ozturk, E., Cinperi, N.C., Kitis, M., 2020. Green textile production: a chemical minimization and substitution study in a woolen fabric production. Environmental Science and Pollution Research 27, 45358–45373. https://doi.org/10.1007/s11356-020-10433-8

Paulson, R.I., 1981. Social Program Implementation: An Incentive Systems Perspective. J Urban Aff 3, 63–74. https://doi.org/10.1111/j.1467-9906.1981.tb00018.x

Paździor, K., Bilińska, L., Ledakowicz, S., 2019. A review of the existing and emerging technologies in the combination of AOPs and biological processes in industrial textile wastewater treatment. Chemical Engineering Journal 376, 120597. https://doi.org/10.1016/j.cej.2018.12.057

Peritore, A.F., Gugliandolo, E., Cuzzocrea, S., Crupi, R., Britti, D., 2023. Current Review of Increasing Animal Health Threat of Per- and Polyfluoroalkyl Substances (PFAS): Harms, Limitations, and Alternatives to Manage Their Toxicity. Int J Mol Sci 24, 11707. https://doi.org/10.3390/ijms241411707

Plakantonaki, S., Kiskira, K., Zacharopoulos, N., Chronis, I., Coelho, F., Togiani, A., Kalkanis, K., Priniotakis, G., 2023. A Review of Sustainability Standards and Ecolabeling in the Textile Industry. Sustainability 15, 11589. https://doi.org/10.3390/su151511589

Roos, S., Jönsson, C., Posner, S., Arvidsson, R., Svanström, M., 2019. An inventory framework for inclusion of textile chemicals in life cycle assessment. Int J Life Cycle Assess 24, 838–847. https://doi.org/10.1007/s11367-018-1537-6

Roos, S., Posner, S., Jönsson, C., Olsson, E., Nilsson-Lindén, H., Schellenberger, S., Larsson, M., Hanning, A.-C., Arvidsson, R., 2020. A Function-Based Approach for Life Cycle Management of Chemicals in the Textile Industry. Sustainability 12, 1273. https://doi.org/10.3390/su12031273

Rovira, J., Domingo, J.L., 2019. Human health risks due to exposure to inorganic and organic chemicals from textiles: A review. Environ Res 168, 62–69. https://doi.org/10.1016/j.envres.2018.09.027

Scarpellini, S., Marín-Vinuesa, L.M., Aranda-Usón, A., Portillo-Tarragona, P., 2020. Dynamic capabilities and environmental accounting for the circular economy in businesses. Sustainability Accounting, Management and Policy Journal 11, 1129–1158. https://doi.org/10.1108/SAMPJ-04-2019-0150

Schenten, J., Führ, M., Kleihauer, S., Schönborn, J., 2019. Traceability as driver for more sustainable chemistry in the global textile supply chains. Curr Opin Green Sustain Chem 19, 87–93. https://doi.org/10.1016/j.cogsc.2019.08.003

Schulte, M.N., Paris, C.M., 2024. Working the system—An empirical analysis of the relationship between systems thinking, paradoxical cognition, and sustainability practices. Corp Soc Responsib Environ Manag 31, 4154–4171. https://doi.org/10.1002/csr.2798

Schymanski, E.L., Zhang, J., Thiessen, P.A., Chirsir, P., Kondic, T., Bolton, E.E., 2023. Per- and Polyfluoroalkyl Substances (PFAS) in PubChem: 7 Million and Growing. Environ Sci Technol 57, 16918–16928. https://doi.org/10.1021/acs.est.3c04855

Sena, M., Rodriguez Morris, M., Seib, M., Hicks, A., 2020. An exploration of economic valuation of phosphorus in the environment and its implications in decision making for resource recovery. Water Res 172, 115449. https://doi.org/10.1016/j.watres.2019.115449

Spadea, S., Farina, I., Carrafiello, A., Fraternali, F., 2015. Recycled nylon fibers as cement mortar reinforcement. Constr Build Mater 80, 200–209. https://doi.org/10.1016/j.conbuildmat.2015.01.075

Swedish Chemicals Agency, 2014. Chemicals in textiles – Risks to human health and the environment.

Swiss, J.E., 2005. A Framework for Assessing Incentives in Results-Based Management. Public Adm Rev 65, 592–602. https://doi.org/10.1111/j.1540-6210.2005.00486.x

Wamsler, C., Schäpke, N., Fraude, C., Stasiak, D., Bruhn, T., Lawrence, M., Schroeder, H., Mundaca, L., 2020. Enabling new mindsets and transformative skills for negotiating and activating climate action: Lessons from UNFCCC conferences of the parties. Environ Sci Policy 112, 227–235. https://doi.org/10.1016/j.envsci.2020.06.005

Wang, C., Song, L., 2021. The Incentive System of the Subject Librarians in the University Library. International Journal of Emerging Technologies in Learning (iJET) 16, 114. https://doi.org/10.3991/ijet.v16i03.20469

Wiesmeth, H., Häckl, D., 2015. Integrated environmental policy: Chemicals and additives in textiles. Waste Management 46, 1–2. https://doi.org/10.1016/j.wasman.2015.10.028

Zhou, X., Belloum, A., Lees, M.H., van Engers, T., de Laat, C., 2022. Costly incentives design from an institutional perspective: cooperation, sustainability and affluence. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 478. https://doi.org/10.1098/rspa.2022.0393

Zhou, X., Zhao, R., Cheng, L., Min, X., 2019. Impact of policy incentives on electric vehicles development: a system dynamics-based evolutionary game theoretical analysis. Clean Technol Environ Policy 21, 1039–1053. https://doi.org/10.1007/s10098-019-01691-3

Ziolo, M., Filipiak, B.Z., Bąk, I., Cheba, K., 2019. How to Design More Sustainable Financial Systems: The Roles of Environmental, Social, and Governance Factors in the Decision-Making Process. Sustainability 11, 5604. https://doi.org/10.3390/su11205604