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Retaining product value in post-consumer textiles: How to scale a closed-loop system

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ABSTRACT

In the face of rapidly growing sustainability challenges, pressure is mounting on businesses to decouple production from virgin resources, reduce waste and phase-out pollution. The Circular Economy (CE) is important for addressing resource efficiency within the textiles sector. In a CE for textiles, clothes would be used more, made to be recycled, and made from safe and renewable inputs. Textiles-to-textiles (T-T) recycling is a key component of a circular textiles industry yet represents only 1 % of global textiles production. This paper sets out to answer how a closed-loop system for recycling post-consumer textiles (PCT) can be scaled. Whilst T-T recycling is a rapidly emerging industry, there is a lack of clarity on the enabling conditions needed to scale significantly throughout the value chain. By means of semi-structured interviews with practitioners participating in textiles CE activities, a holistic analysis of the barriers and enablers at all stages of the value chain has been conducted. The paper concludes with practical recommendations addressing each T-T supply chain actor. It makes an important contribution to understanding how actors in the circular value chain, policymakers and convening bodies can act in concert to successfully scale a system for collecting and recycling PCT.

Glossary of terms

Bring-banks Metal containers placed in streets, business centres or recycling centres where citizens can bring unwanted apparel.

Circular trade (CT) Trade transactions that contribute to circular economy activities. This includes the trade in circularity-enabling goods and services; second-hand goods for reuse, repair, or recycling; secondary raw materials and waste that can be safely recovered.

Crème The Faction of high quality, gently used clothing that is in excellent condition and retains a high resale value.

Digital product passport (DPP) Mechanism/tool for collecting and sharing product data throughout its entire lifecycle used to illustrate a product's sustainability, environmental and recyclability attributes.

Disruptor An element present on a textile product, such as buttons and zips. These disrupt the recycling process and generally need to be removed before the product is suitable as feedstock for recycling.

Downcycling Mechanically recycling textiles to create a product that is of lower value than the original (e.g. Cutting or shredding clothing to make mattress filling).

Fractions Categories by which collected used textiles are sorted for different reuse and recycling purposes and sold on different local and global markets.

Just transition Term used to describe the transition to a climate-neutral economy while securing the future and livelihoods of workers and their communities.

Low value textiles For the purpose of this research, non-rewearable and low-value rewearable textiles are referred to as low-value textiles.

Mechanical recycling The process by which textiles are cut, shredded, and opened into fibres that are usable for diverse applications.

Near infrared (NIR) NIR sorting is used commonly in the waste industry to recover materials of value from mixed streams. The technology uses differences in the wavelengths of infrared

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light that is reflected by polymers with different chemical structures.

Post-consumer textiles (PCT) Textiles that have been disposed of after consumption and use by the citizen or end-users of commercial or industrial institutions, processed by a specialised textile sorter.

Post-industrial waste The (textile) waste generated from industrial processes. This is generally clean and of consistent fibre composition and is therefore easier to use as feedstock for new textiles.

Take-back scheme Program organized by a manufacturer or retailer, to collect used products or materials from citizens.

Textiles-to-textiles recycling (T-T recycling) Textile recycling is the process of recovering fibre, yarn, or fabric and reprocessing the material into new, useful products. Textile waste is split into pre-consumer and post-consumer waste and is sorted into five different categories derived from a pyramid model.

1. Introduction

The transition to a Circular Economy (CE) in the textile and fashion industry has gained significant attention in recent years. The literature on textile recycling in a CE encompasses several key themes, including environmental sustainability (Mora-Sojo et al., 2023), consumer attitudes (Casson et al., 2023), supply chain management, and the role of technology in enabling circularity (Schmutz & Som, 2022). Recent studies have explored the challenges and dilemmas faced in transforming the fashion and textile industry, emphasizing the need for sustainable pathways and innovative design strategies to support circularity. Although there are many definitions of the CE, the main aim is to replace the 'end-of-life' concept with reducing, reusing, recycling, and recovering materials in production/distribution and consumption processes (Kirchherr et al., 2017). Within a CE, clothing and other textile products would be used more, designed to be recycled, and manufactured from safe and renewable materials (Wagner and Heinzel, 2020). This approach would require processing textile waste to create new textile products, thereby closing the loop in the textile industry and reducing the environmental impact of textile production. This process is referred to as textiles-to-textiles (T-T) recycling and involves collecting textile waste, such as discarded clothing and fabric scraps, and processing it to create new fibres or textiles for reuse in the production of clothing, home textiles, or other fabric-based products (Sandvik and Stubbs, 2019).

The detrimental environmental impacts of fashion's linear business model are well documented. Apparel production is responsible for approximately 6.7 % of global greenhouse gas emissions, and it is estimated that the sector produces 92 million tonnes of waste annually (Quantis, 2018; Niinimäki et al., 2020). The prevailing linear system is characterized by unsustainable resource extraction and pollution. The rise of fast fashion has contributed to escalating textiles fibre production, which globally doubled from 58 million tonnes in 2000 to 113 million tonnes in 2021 and is expected to reach 149 million tonnes by 2030 (Textile Exchange, 2022).

Textiles-to-textiles (T-T) recycling is a key component of a circular textiles industry yet represents only 1 % of global textiles production (Textile Exchange, 2022). While the existing literature and industry reports have provided valuable insights into the potential for CE practices in the textile industry, including citizen participation into the CE for textiles (Wagner and Heinzel, 2020), including consumer acceptance of recycled materials (Jäämaa and Kaipia, 2022), increasing post-consumer textiles (PCT) collection rates and improving sortation (Cura et al., 2021; EuRic, 2021; Interreg, 2020)) there is a gap concerning how to scale a whole system to support T-T recycling. Additionally, there is a need for more research on the practical implementation of CE principles and practices in the textile industry (Purvis et al., 2023; Moran et al., 2021; de Oliveira Neto, 2019). Understanding the barriers and enablers for the transition to a CE in diverse socio-economic contexts can inform targeted strategies for sustainable textile recycling and circular fashion practices (Hartley et al., 2022).

This research aims to address these gaps in the literature by taking a practitioner perspective to address the question 'What enabling conditions, infrastructure and incentives are required to scale a closed-loop system for the recycling of post-consumer textiles?'

To help answer this question a review of the literature was conducted using the following search terms: textiles collection in Europe, textiles recycling technology, textiles CE, CE investment, CE regulations, post-consumer textiles sorting, and fashion design for circularity. The knowledge and understanding gained from this were used to inform the questions for semi-structured interviews that were conducted with experienced professionals representing various stages of the circular value chain in the textile industry. Thematic analysis was used to identify systemic enablers, barriers, and potential solutions, resulting in a comprehensive understanding of the experiences and perspectives of the interviewees (Kirchherr et al., 2018). Although this study focussed on the experiences of a small sample from a European context, the insights gained from the interviews can inform targeted strategies and actions to address systemic enablers and barriers in the circular value chain across the textile industry.

The remainder of this paper is organized as follows: Section 2 provides an overview of existing literature on textile recycling. Section 3 outlines the research methods employed. Section 4 outlines the findings of the research. Finally, Section 5 suggests four key, interconnected enablers for scaling T-T recycling that serves as the basis for stakeholder-specific recommendations for action. Finally, Section 6 provides a concluding summary with suggestions for further research.

2. Review of the literature

There is an extensive body of extant literature on textile recycling. A review of the literature was conducted using the following search terms: textiles collection in Europe, textiles recycling technology, textiles CE, CE investment, CE regulations, post-consumer textiles sorting, and fashion design for circularity. Papers were selected to provide a thorough understanding of the current context of the research. This informed the methodology for practitioner research, including selecting interviewees and the corresponding questionnaire. Additional key research in the field is noted in Appendix 1. The review begins by delving into the role of textiles recycling in a CE, as envisioned by the Ellen McArthur Foundation. It then explores various technologies for recycling textile fibres, including mechanical, thermal, and chemical processes, each with its advantages and limitations. Despite technological, systemic, and economic barriers, the potential for scaling recycling technologies commercially is discussed, highlighting its positive economic, social, and environmental impact. The subsequent sections delve into the business case for Textiles-to-Textiles (T-T) recycling, the regulatory context, strategies to increase post-consumer textile (PCT) collection, and the importance of designing for circularity.

2.1. The role of textiles recycling in a circular economy

The role of textiles recycling in a circular economy is crucial for addressing the environmental impact of the fashion industry. The Ellen McArthur Foundation's vision for a circular economy for fashion is one that is restorative and regenerative by design and provides benefits for business, society, and the environment. In a circular system, clothes are kept at their highest value during use and re-enter the economy after use, never ending up as waste. This vision can be realised by achieving four ambitions (EMF, 2017). The pursuit of four key ambitions - phasing out harmful substances, increasing clothing utilization, radically improving recycling, and making effective use of resources - underpins this vision.

Of these, the ambition to radically improve recycling presents the greatest challenge (Schmutz & Som, 2022). Globally 87 % of total textiles are landfilled or incinerated following first use, representing a loss of resources valued at more than USD 100 billion annually (EMF, 2017). European citizens dispose of 60–65 % of their used clothing in domestic general waste. Of the 30–35 % that is donated or collected, 40 % is exported for resale, which is ultimately dumped or burnt in poorer countries (McKinsey, 2022).

Material flows within the CE for fashion are shown in Fig. 1. In accordance with the waste hierarchy, low-value textiles are recycled following extended use. Increasing T-T recycling rates begins with product design, and then requires changes in the post-consumer collection, sortation, aggregating and preparation for recycling practices. Finally, access to and adoption of recycling technologies must be improved.

Textile fibre recycling employs three primary technologies: mechanical, thermal, and chemical. Mechanical recycling, characterized by maturity and cost-effectiveness, offers the advantage of processing diverse textile waste streams at variable scales (Piribauer and Bartl, 2019). In mechanical recycling, to achieve yarn of acceptable quality, spinnable fibres must reach a certain length. For natural fibres, the fraction of spinnable fibres is 5–20 % of the input, while for polycotton or polyester, it ranges from 25 to 55 % (Gulich, 2006). Therefore, recycled fibres are often blended with virgin material to achieve the fibre length and quality required. Additionally, challenges include the inability to separate fibre blends, the retention of hazardous chemicals like additives, dyes, or finishes, and a lack of repeatability as the quality degrades with reduced fibre length (de Oliveira Neto, 2019).

For mono-fibre synthetic textiles, thermo-mechanical methods provide a recycling avenue. (Piribauer et al., 2021) However, this approach has limitations, such as a reduction in quality, retention of colour, and the possibility of chemicals in the feedstock persisting through the process (Zhou et al., 2023).

Technologies for chemically recycling non-blended cellulosic and synthetic textiles have undergone intensive development in recent years. Chemical recycling of cellulosic textiles is now deployed at an industrial scale with several innovators now able to recycle post-consumer waste (Textile Exchange, 2022). Recycled post-consumer nylon fibres also have become commercially available on a small scale. The key limitation of chemically recycling technologies has been the requirement of non-blended and uncontaminated feedstock. However, new chemical and thermo-chemical technologies currently under commercial development can separate and recapture polyester from discarded low-value materials to produce virgin-like output material. The main advantages of chemical recycling are that the recycled material can be purified to obtain a pure, colourless polymer of virgin-like quality (EU, 2021 Study on effectiveness of textile fibres recycling). This means that the process is repeatable.

Although the T2T recycling technology is available for mono-fibre and some blended textiles, recycling post-consumer textiles at scale bears several barriers (Hartley et al., 2022). Suitable feedstock supply is still relatively limited and the removal of non-textile materials like trims is problematic for recyclers (Hey Fashion, 2022). Currently costs for chemical recycling are still relatively high compared to processed virgin fibres when the feedstock material is heavily contaminated additional purification steps might be required which further increases the production costs. In addition, energy and chemical use are intensive.

Despite remaining technological, systemic, and economic barriers, it is possible to scale recycling technologies commercially given the right enabling conditions. Businesses that could serve as evidential case studies are noted in Appendix B. This would decrease the demand for virgin fibres, reducing the pressure on natural resources (Suárez-Eiroa et al., 2019).

2.2. *The business case for textiles-to-textiles recycling*

Textiles-to-textiles (T-T) recycling and involves collecting textile waste, such as discarded clothing and fabric scraps, and processing it to create new fibres or textiles for reuse in the production of clothing, home textiles, or other fabric-based products (Sandvik and Stubbs, 2019). In the prevailing environment, the weak economics of T-T recycling contributes to a sub-scale activity. However, the literature reviewed made a strong emerging business case for T-T recycling within Europe as regulation is anticipated to address some economic limitations, and brands are increasing CE commitments (Hedrich et al., 2021; McCauley and Jestratijevic, 2023).

One survey suggested that over half of the European brands anticipated that more than 30 % of their apparel would be produced with recycled fibres by 2025 (Imran et al., 2021). This suggests increasing demand for recycled fibres, yet the supply fibre deficit is forecast to be

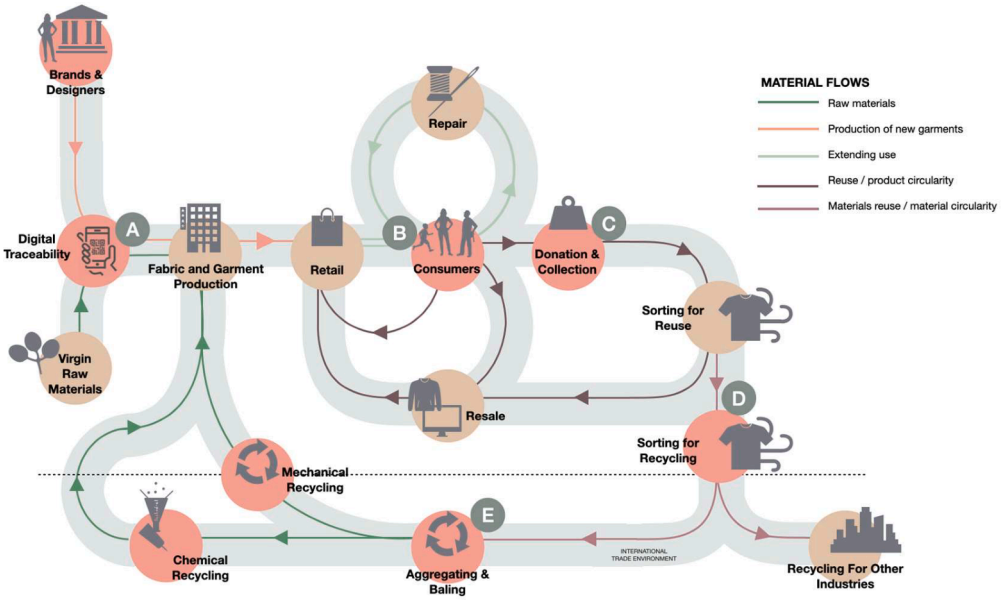

Fig. 1. A circular economy for fashion.
Note. Adapted from *The Circular Fashion Ecosystem: A Blueprint for the Future*. Institute of Positive Fashion.

60–70 % by 2030 (McKinsey, 2022). Recycling volumes in EU-27 and Switzerland have the potential to increase from <1 % of gross household textile waste in 2020 to 18–26 % by 2030. This would require an estimated investment of EUR 6–7 billion to scale up collection, sorting, and recycling infrastructure (McKinsey, 2022).

A further study (BCG, 2020) identified financing barriers specifically at the new technology development stage and the commercialisation stage. These are more acute for the T-T recycling segment, given the asset-intensive nature of the technologies involved (Sandvik and Stubbs, 2019). Additionally, venture capital & private equity investors do not understand this sector well, as it is not associated with benefitting from technological innovation.

Reliable transition support, for example, funding from Extended Producer Responsibility (EPR) schemes or brand-funded green premiums, will be required to justify economics until the CE for textiles is mature (Purvis et al., 2023). Some progressive large brands have shown an appetite to provide new technology development funding through their corporate venture capital arms. There is also a significant role for blended finance to leverage high-risk capital from philanthropic funds, brands etc., to support larger funding requirements for commercialising new technologies. Green financing incentives driven by regulations can also help support larger-scale projects (BCG, 2020)

Financial regulations also have a direct impact on investment accessibility: The *EU Taxonomy*, is a comprehensive classification system for what qualifies as green investment, and the *Corporate Sustainability Reporting Directive (CSRD)* standardises and regulates corporate sustainability reporting. Business sustainability risk effectively becomes a financial risk, as investors increasingly make investments dependent on sustainability performance (Bernow et al., 2017). It could be argued that investors are a growing enabler of systemic change, in conjunction with effective regulation.

If successfully implemented scaling T-T recycling activities in Europe is forecast to result in an economic upside of EUR 1.5bn – 2.2bn alongside a social and environmental impact valued at EUR 2–2.5bn (McKinsey, 2022). While regulatory changes, technological developments and financing enablers are emerging, how to match supply and demand by creating viable businesses throughout the circular value chain requires additional research.

2.3. Regulatory context

While recognising the economic importance of the textiles sector, European regulators see an urgent need to mitigate the environmental and social burden it represents. As part of the EU Green Deal's Circular Economy Action Plan (CEAP), the European Commission has initiated the *EU Strategy for Sustainable and Circular Textiles* (Directorate-General for Environment, 2022). This comprehensive framework is intended to create a level playing field with quasi-global applicability and to become a regulatory gold standard which other jurisdictions would also adopt.

The forthcoming regulatory framework within the EU aims to address barriers to scaling Textiles-to-Textiles (T-T) recycling by implementing key policy areas. These include mandatory extended producer responsibility (EPR) schemes and requirements for recycled content in new textile products. Additionally, the framework will establish mandatory standards for the repairability and durability of textile products, reflecting a commitment to promoting longevity and sustainability. It introduces new rules on green claims, encompassing environmental and social footprint, recycled content, and more, with indications that some aspects may become mandatory within a digital product passport (DPP) scheme. Furthermore, the regulatory framework proposes rules that either prohibit or discourage the destruction of unsold or unused clothes, aligning with the circular economy principles. This comprehensive set of policies forms a cornerstone for addressing challenges and fostering the growth of T-T recycling in the EU.

The EU Textile Strategy outlines an implementation timeframe ranging from twelve to forty-eight months, with specific legislations, including the EU Taxonomy and sustainable products regulation planned for potential enforcement as early as 2023 (Directorate-General for Environment, 2022). Even if only partially executed, this regulatory framework possesses the capacity to significantly transform the textile market. Notably, the EU, holding a substantial 25 % share of the global sales value (CBI and M-Brain, 2019; Sabanoglu, 2022), remains a pivotal player in steering the course of sustainable practices within the textile industry.

2.4. Increasing post consumer textiles collection

Collection rates for PCT vary significantly across Europe: Germany is at 75 %, France at 38 %, Italy at 11 %, (European CEAP 2016). France is the only country with a n EPR scheme funding the collection and management of PCT. 69 % of PCTs collected in France come from bring-banks, 24 % from retail take-back schemes and recycling centres combined, and only 0.5 % from door-to-door charity collections (Eco TLC, 2015). This could indicate that even under an exemplary scheme, the missed opportunity is a convenient home collection. Citizens most commonly donate PCT to family and friends or to charities, which play a key role in both collecting and sorting (ECAP, 2018). Local authorities generally control bring-banks through contracts with charities or private companies (Woodard, 2015).

Increasing PCT collection requires citizen participation (Cai et al., 2022), driven by awareness of the environmental and social benefits (Kumar Jena and Sarmah, 2015). Fashion retailers are increasingly introducing take-back schemes. However, collection rates are often meagre even when financial incentives are offered. One way for brands and retailers to increase collection rates is to view their customers as suppliers, necessitating a new approach to customer relationship management (Kant Hvass and Pedersen, 2019). This approach seeks to engage customers as responsible partners in the value-creation process and motivate them to be active participants in the CE (Boons and Lüdeke-Freund, 2012; Lüdeke-Freund and Florian, 2014)).

Increasing collection rates will require significant citizen behaviour change supported by appropriate messaging, incentives, and convenient donation modes. Greater supply will need to be matched by increased capacity in reverse logistics, sorting and recycling. Practitioner experience would provide insight into what changes would enable collection rates to increase in tandem with related infrastructure.

2.5. Designing for circularity

A radical redesign of products and input materials is required to ensure the feasibility of scaling T-T recycling (Wagner and Heinzel, 2020). Designers must carefully consider several factors: the choice of recycled materials (mono-fibre or recyclable fibre blends), product construction methods, trims, and surface treatments (Karell, 2018).

Recycling efficiency and feasibility is dependent on product recyclability. However, recyclability is rarely considered in the design process, which results in one third of garments being unsuitable for closed-loop recycling (Köhler et al., 2021; Wang, 2006). Although the CE currently is regarded as an indispensable pathway forward to address fashions unsustainable resource use, design for recyclability does not yet play a primary role in fashion companies sustainability ambitions and approaches. (Karell and Niinimäki, 2020).

The literature reveals six dominant challenges in enhancing design for recyclability (Köhler et al., 2021; Watson et al., 2017; EEA, 2019). These challenges include a lack of circular design knowledge, limited influence of designers on material and design decisions due to the balancing of cost, aesthetics, functionality, and recyclability, company mindset and strategy, the pressure for rapid product speed to market, consumer preferences for certain aesthetics, novelty, and functionality achieved through product complexity, including material mixes, blended fibres, and intensive chemical processes. Moreover, the fragmented nature of supply chains poses difficulties in achieving raw

material traceability. Overcoming these challenges necessitates insights from practitioners who can provide valuable perspectives on effective solutions.

2.6. Implementing a closed-loop system in the global fashion sector

There is tension between Europe's textiles' circularity goals and the reality of a sector in which international trade relationships predominate. Although Europe is a major producer of textiles, 72 % of the European apparel industry's €147 Billion sales in 2021 were derived from the sale of imported goods. China, Bangladesh, Turkey, India and Cambodia, together account for 75 % of imports (Euratex, 2022; Lu, 2022).

Households and industries within the EU 27 countries create an estimated 7–7.5 million tons of unwanted textiles per annum. The top importers of used clothing are Ghana, Ukraine, Pakistan, United Arab Emirates and Nigeria, accounting for only 19 % of this fragmented market (*Used Clothing | OEC*, 2020). International trade in PCT extends the life of apparel and is often of economic importance in recipient countries (Changing Markets Foundation et al., 2023; Wright & Greenwood, n.d.). However, as the quality of clothing has decreased, traders in recipient countries report that 30–65 % of used clothing bought in bales is unsaleable and is therefore burnt or dumped immediately.

If PCT textiles collection reaches Europe's 2030 target of 80 %, this will far exceed reuse and recycling capacity. New EU rules are intended to restrict the export of textile waste to non-OECD countries with the willingness and capacity to manage it sustainably (Directorate-General for Environment, 2022). Yet there is currently no distinction between textile waste and second-hand textiles in EU product classifications used for export declarations (European Environment Agency, 2023). Questions also remain about the economic impacts of trade policy in countries that produce apparel and textiles and those that import used apparel (Repp et al., 2021). Practitioner experience could provide insight into effective Circular Trade (CT) policies that could create opportunities for PCT to be traded internationally in ways that support a just transition to a CE. The EU Strategy for Sustainable and Circular Textiles creates a strong framework for increasing T-T recycling (Directorate-General for Environment, 2022). However, effective implementation requires consultation with actors throughout the value chain.

2.7. Summary

The review of the literature provides further understanding of the challenges and opportunities in textile recycling, shedding light on the path towards achieving a closed-loop system. Expanding on the role of textiles recycling in a CE, the Ellen McArthur Foundation's vision emphasizes ambitious goals, including the need to radically improve recycling to address the staggering 87 % of global textiles ending up in landfills or incinerators (EMF, 2017). The literature explores various recycling technologies—mechanical, thermal, and chemical—acknowledging their advantages and limitations (EU, 2021 Study on effectiveness of textile fibres recycling). Despite the identified technological, systemic, and economic barriers, the review recognizes the potential for significant positive economic, social, and environmental impacts if recycling technologies are scaled commercially (McKinsey, 2022).

The business case for Textiles-to-Textiles (T-T) recycling within Europe emerges as a focal point in the literature (Hedrich et al., 2021; McCauley and Jestratijevic, 2023). The weak economics of T-T recycling, compounded by a forecasted supply fibre deficit of 60–70 % by 2030, underscores the need for financial incentives and transition support (McKinsey, 2022). The regulatory landscape, particularly the EU Strategy for Sustainable and Circular Textiles, is recognized as a robust framework but prompts the question of its effective implementation (Directorate-General for Environment, 2022).

Considering PCT collection, the literature emphasizes the importance of citizen participation, highlighting the challenges in increasing collection rates, the role of fashion retailers, and the necessity for behavior change (Cai et al., 2022; Kant Hvass and Pedersen, 2019). Designing for circularity emerges as a critical aspect, with identified challenges including the lack of circular design knowledge, limited influence of designers, and fragmented supply chains (Karell and Niinimäki, 2020; Köhler et al., 2021). The tension between Europe's circularity goals and global trade dynamics, where international trade relationships predominate, is discussed, raising questions about the economic impacts of trade policies (Euratex, 2022; Directorate-General for Environment, 2022).

In addressing the question of enabling conditions, infrastructure, and incentives required to scale a closed-loop system for post-consumer textile recycling, the literature review recognizes the need for practitioner insights. While existing frameworks, regulations, and technology provide a foundation, understanding the practical challenges and solutions from a practitioner's perspective emerges as a potential gap in the literature. Insights from those actively engaged in the field could offer valuable perspectives to bridge this gap and inform effective strategies for scaling closed-loop systems in textile recycling.

3. Methodology

3.1. Research design and methods

This research paper seeks to answer the research question: What enabling conditions, infrastructure and incentives are required to scale a closed-loop system for the recycling of post-consumer textiles?

The methodological steps for this study are depicted in Fig. 2. The authors conducted a structured review of relevant academic and practitioner literature using the following search terms: textiles collection in Europe, textiles recycling technology, textiles CE, CE investment, CE regulations, PCT sorting, and fashion design for circularity. The literature review commenced in June 2022. To our knowledge, academic literature published prior to that year generally did not address a holistic view of all T-T value chain partners, and related systemic challenges to scaling. More recently, multiple reports providing insight into the opportunities and complexity of T-T recycling have been published, indicating a growing interest in this research area.

Due to the identified gap in the existing literature, the following research objectives were identified to provide a comprehensive picture of the systemic barriers and enablers:

- Understand the various actors involved in the scaling of a closed-loop system for T-T recycling.
- Assess the understanding of regulatory aspects in shaping the circular value chain for textiles from a variety of stakeholders.
- Identify existing initiatives and challenges to scale T-T recycling.
- Identify and review the maturity of T-T recycling technologies.
- Make recommendations for stakeholders.

3.2. Data collection and analysis

Following a review of the literature, semi-structured interviews were chosen as a valuable method for collecting data to answer the research question. Interviews allow for in-depth exploration of the research question by providing an opportunity for open-ended conversations. Participants can elaborate on their experiences, perspectives, and insights, offering nuanced and detailed information. This method is particularly effective for exploring the intricate interplay of factors within the specific context of post-consumer textile recycling. Follow-up questions can be asked to delve deeper into specific areas of interest, ensuring a comprehensive exploration of the research question. Practitioners from across the value chain were selected to further understand the enabling conditions, infrastructure, and incentives required to scale

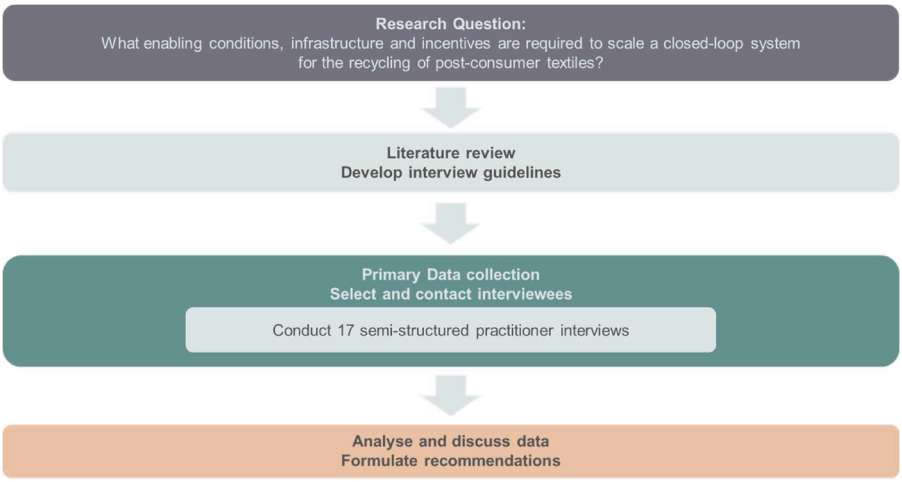

Fig. 2. Research design.

a closed-loop system for the recycling of post-consumer textiles. Europe was the focus of the study due to incoming legislation that supports a circular textiles system (Kirchherr et al., 2018). Interviewees were all involved in T-T recycling or related technology or infrastructure in the European market. Although the sample size was small, the interviews provided rich layered, intricate, detailed, and nuanced data.

An interview protocol included a set of predetermined questions or topics to be covered during the interview, along with guidelines on how to ask the questions, probe for additional information, and record responses. The questions were designed to explore the multifaceted aspects of the research question and were informed by the findings of the literature review. The questions were structured to gather comprehensive information regarding business details, scaling intentions, waste sorting processes, logistics, partnerships, regulation, and the impact of design on recycling. For some value chain stakeholders, the questions were adapted to gain a deeper understanding on barriers and opportunities in their area of business. In addition, more informal discussions during the call aided openness and our depth of understanding. The interview protocol with example questions can be found in the Appendix.

Interview participants included at least two representatives from each stage of the circular value chain. All interviewees have significant experience at a senior level in their field in either participating in aspects of scaling closed-loop recycling or in facilitating and financing circular economy (CE) initiatives more broadly. Additionally, each met one of the following criteria: early adopters or innovators in textiles closed-loop recycling, individuals with experience in effecting systemic change in the CE for textiles. Interviews were conducted via recorded video calls and transcribed. Table 1 details the seventeen interview participants alongside their organisation type, location, and role of interviewee.

Thematic analysis was a flexible and robust method of analysing interview data (Clarke et al., 2013). Emerging patterns and themes provided a deeper understanding of the experiences, perceptions, and perspectives of the interviewees. The process began with familiarisation of the interview transcripts to gain a comprehensive understanding of the content. Next, initial codes were generated to categorize segments of the data that were relevant to the research question. Initial coding identified 227 data entries, including 64 enablers, 85 barriers, and 39 potential solutions. Once initial coding was completed, the authors began to search for overarching themes or patterns within the coded data. Once the themes had been reviewed and refined, they were named to reflect their content and meaning. The final step in the process of thematic analysis involves reporting the results of the analysis. These are presented in the following section.

Table 1
Interview participants – organisation type, location, and role of interviewee.

#	Organisation type	Location zone (s)	Role of Interviewee
1	Textile Recycler	United Kingdom	Managing Director
2	Textile Recycler	Multinational	Founder
3	Charity collector	United Kingdom	Senior Manager
4	Charity collector	United Kingdom	Senior Manager
5	Charity collector	Spain	General Manager
6	Textile Recycling Innovator	Finland	Chief Sustainability Officer
7	Textile Recycling Innovator	Sweden	Strategy Director
8	Digital Technology and Infratructure Provider	Germany	Commercial Director
9	Digital Technology Provider	Multinational	CEO
10	Recycling Technology Provider	Hong Kong	Marketing Manager
11	CE Focussed Private Equity Fund	United Kingdom	Investor
12	Circularity MSI	United Kingdom	Senior Sector Specialist
13	Global Impact Organisation	Netherlands	Capacity Development Prog Lead
14	Disruptor Brand	Switzerland	LCA specialist
15	Global Brand	Multinational	Vice President
16	Recycling and Waste Management Services	United Kingdom	Director
17	Sustainable Apparel Supply Chain Consultancy	United Kingdom	Supply Chain Executive

4. Interview data analysis and interpretation

The coded data entries were categorised into 5 overarching themes, which are presented in the analysis. Relevant insights from the interviews have been included to illustrate the findings. The discussion further delves into both barriers and enablers to scaling of a closed-loop system for PCT recycling.

4.1. Scaling technology and infrastructure

To scale T-T recycling, it is imperative to establish compelling business cases, including the collection and sorting of growing fractions of low-value textiles. Additionally, there is a need for aggregating volumes of textiles with similar fibre compositions and preparing low-value textiles for recyclers in accordance with various specifications. Furthermore, the scaling of T-T recycling necessitates the development and implementation of new textile recycling technologies beyond the

proof-of-concept or pilot facility stage.

Practitioner interviews highlighted a weak business case for increasing capacity for T-T recycling and related infrastructure. This contrasts with the more optimistic view emerging from the literature, which could be accounted for by the involvement of brands and consultants, who have a vested interest in the success of circularity as it provides legitimacy to continued economic growth. However, there are very clear steps needed to reduce barriers and enable these businesses to drive profit and attract investment.

4.1.1. Barriers

The economic viability of collecting and sorting depends on revenue generated by the resale of good quality PCT. Participants agreed that the viability of collecting low-value textiles heavily relies on tax incentives, donations and volunteer labour provided to charities. Outside of the charitable sector, the collection is at best a contribution margin to resale businesses (P8). Eight participants confirmed that this dynamic creates a disincentive for increasing the collection of low-value textiles. "We, brands, governments, all talk about textile circularity in Europe, but if there is no business case to collect more textiles, then there is absolutely no point talking about circularity" (P13). P16 agreed, "In the case of low-value PCT, there is no mechanism to pay for a collection service, and the waste does not have residual value. This absence of revenue generation mechanism means we have no reason to engage in the collection of textile waste".

The first sortation of PCT remains a costly manual process. Sorting for fibre composition can be automated by technology based on near-infrared fibre identification. However, this equipment is only financially viable for larger organisations, as setup costs are substantial (P4, P12) and considerable expertise is required for efficient operations (P2, P4). Innovators in recycling had difficulty attracting investment in the early stages. A now-scaled T-T recycler with proven T-T recycling technology spoke of a "funding desert" (P7) before building a first commercial-scale plant. Finally, brands wanting to increase the mix of recycled fibres in their products face higher prices as the cost of virgin fibres does not account for environmental or social externalities (P15).

4.1.2. Enablers

The implementation of the *EU Strategy for Textiles* should overcome some commercial viability hurdles to achieving scale while opening access to financing as investors face more predictable conditions. However, the business case for collecting a greater fraction of low-value textiles is dependent on a funding source, P16 believed the right type of carbon taxation or EPR schemes would be effective.

Sorting low-value textiles for recycling still relies heavily on manual intervention. Hence a substantial proportion of sorting occurs in low-cost countries such as India and Pakistan. Near-infrared sorting technology could make it viable to sort a greater fraction of low-value textiles in locations where large volumes of PCT are already aggregated. EPR is one mechanism that could fund this both within and outside of Europe.

Recycling innovators found that fashion brands providing early-stage venture capital and committing to buying recycled textiles had been critical to building a business case for scaling operations. In the case of P7 once early brand investment funded proof-of-concept, additional funding was more readily attracted from institutional investors. P11 explained that the challenge is to match sufficiently available capital, with scalable businesses to invest in (i.e., which can demonstrate post-product market fit), rather than a shortage of available capital.

Finally, there was a consensus that building a compelling business case for each stage in scaling textiles recycling requires collaboration across the value chain. Success is dependent on actors in all parts of the system sharing commercial risk and regulation, creating the right conditions to facilitate commercial viability.

4.2. Regulation as an enabler

In all interviews, regulation was emphasized as an important enabler of a CE for textiles. For instance, P2, an active participant in policy shaping, emphasized the "need to create legislative frameworks to discourage reliance on virgin materials" and promote the integration of post-consumer materials into new products. The interviews collectively articulated specific requests aligned with a collaborative approach in implementing the EU Strategy for Textiles framework. While not explicitly attributed to individual interviewees, these recommendations mirror the broader sentiments expressed during the discussions with participants. Key suggestions include a phased increase in mandatory recycled content in new products, the establishment of a level playing field through unified and compulsory rules for all market participants selling in Europe, the incorporation of the true cost of textile products (encompassing environmental impact pricing and recycling) through mechanisms like carbon taxation or Extended Producer Responsibility (EPR), the enforcement of mandatory collection mechanisms for post-industrial textiles and post-consumer textiles (PCT), and the establishment of clear regulations governing repairability and durability to enhance the overall quality of collected materials and items. This approach addresses concerns about the specificity of participant references, presenting a comprehensive overview of stakeholders' perspectives on policy implementation within the EU Strategy for Textiles framework.

Linear trade rules, identified as impediments to a global CE, were flagged as problematic, with primary definition falling under World Trade Organisation (WTO) regulations. Nevertheless, the incorporation of circularity into the implementation of the European Waste Framework Directive was recognized as a pivotal facilitator.

Like the previously mentioned recommendations, the need for forums where regulators can interact with stakeholders across the circular value chain for recycled textiles was underscored. The effectiveness of policy design, ensuring a simultaneous scaling at all supply chain stages, becomes imperative. While not directly linked to specific interviewees, these observations resonate with the overarching perspectives shared throughout the discussions. Ensuring an alignment between the supply and demand for recycled textiles at every stage of the value chain emerges as a critical factor in successfully scaling the system.

4.3. Implementing design for circularity

Four participants had experience implementing the principles of circular design in a commercial environment, and P9 provided additional insight into the role of traceability technology and effecting change in the supply chain. The overarching message is that implementing the circular design at scale remains challenging. Although all agreed with the principles as set out in the literature review, in practice implementing these requires a substantial shift in normalised practice and consumer expectations.

4.3.1. Barriers

Three main barriers to circular design were identified: Product design limitations, consumer expectations and corporate culture.

Product design and development are often linked to tight deadlines and cost pressures. This can lead to poor material choices such as multi-fibre compositions or qualities that lack durability. Mono-materiality and recycled content can be difficult to source for all product components, which can result in supply limitations and extended lead times. P15 and P14 also highlighted the price premium for mono-fibre and recycled qualities.

Meeting consumer expectations whilst designing for physical and emotional durability, and recyclability remains a challenge. Consumers are accustomed to the comfort, performance and often lower prices associated with blended fibres (P14 & 15). "It's a big challenge for the material team to find a solution to allow for the same functionality but

still meeting circularity requirements, and then also create a product that is nice from an aesthetic perspective, and even also maybe change consumers' mindsets to make a recyclable [product], a sexy [product]" (P14). Designing for emotional durability is challenging in the current fashion system where consumers have been encouraged to expect constant novelty, revolving trends, and competitive prices.

P12 and P15 noted that consumption patterns are changing at a slow pace. The data on consumers' preference to purchase sustainable products shows a positive trend. However, participants noted a gap between the values expressed and purchasing behaviour. "There's still a cognitive disconnection between awareness that collective misbehaviour is driving an environmental crisis and an awareness of personal shopping habits. The two aren't necessarily cross-informing one another yet" (P15). Customers are often unwilling to pay the premium for products designed to meet circularity principles. "There's no marketing message so powerful that it will convince a consumer to pay $40 more for anything".

Lastly, corporate culture and capacity were seen as barriers. Unsuccessful change management and lack of buy-in from management are obstacles. Uninformed colleagues, and resistance within teams incentivised by outdated metrics, blocks circularity ambitions, "Sustainability can get stuck in head office and is hindered by lack of engagement, communication, and education across departments and value chains" (P12). P12 and 15 suggested that the environmental impacts of materials and design decisions are not always understood by product teams. "When you're throwing a lot of change at your cross-functional colleagues, without appropriately socialising the necessity for the change. it's really a mindset shift. Everybody involved in the garment is adapting to those constraints and just educating everybody on how deep those constraints run and what a fundamental shift in their approach to the business, to their design philosophy, to how we manufacture things" (P15).

4.3.2. Enablers

Adopting circular design principles can facilitate the scalability of T-T recycling by incorporating pertinent technologies, fostering collaboration along the value chain, and engaging customers.

Technological advances in T-T recycling and better data to make informed design choices are considered vital enablers. However, P15 believed "technology will not be the silver bullet to solve design-related questions to circularity. More discipline in the choice of mono–materiality would already drive much change". P14 suggested that it would be valuable to integrate material databases, including sustainability data into digital design tools, as is common practice in the automotive industry.

Supply chain transparency and materials traceability, facilitated by digital technology, are highlighted as strong enablers for circular design. Mapping waste streams throughout production processes could increase the availability of post-industrial waste, which is easier for recyclers to utilise and often needed to blend with PCT.

Brands and recyclers that want to increase recycled content need to engage consumers in the conversation to change purchasing behaviour. P14 and 15 found that strong marketing campaigns with educational value, as well as circularity role models and ambassadors, were effective communication channels to influence consumer behaviour. In P15's experience, simple marketing messages about more sustainable products are more impactful, and e-commerce is a more effective channel for providing more detailed information.

4.4. Collaboration across a global system

A theme emerging from the interviews is the importance of designing sortation and recycling strategies that align with the current material flows and international trade networks for raw materials, textiles, and new and used apparel. Europe cannot create a circular economy in isolation. The practitioners reasoned that CT rules and circular solutions could be optimised to create economic benefits whilst reducing negative social and environmental impacts. CT is an under-explored area within the literature reviewed, which could be criticised for taking a Eurocentric viewpoint. Yet working with the material flows in a global sector will be critical to a successful and just transition to a CE.

4.4.1. Barriers

Opportunities to scale a closed-loop system for the recycling of PCT are currently hindered by international trade rules and classifications designed for a linear economy, poor sorting practices, and poor accountability and traceability throughout the value chain.

Current WTO rules and trade classifications poorly differentiate between *waste* materials as feedstock and true *waste* (Wetterberg et al., 2022). P2 and P14 had experience with trade rules and Harmonised System of product classifications making the execution of circular products challenging. For example, exporting sorted *waste* materials to a specialist manufacturer to use as feedstock required considerable knowledge of how to comply with trade rules to avoid rejection at customs.

Producer countries typically impose import tariffs on PCT. According to P1, in Africa, Chinese influence has led to high tariffs on used clothing imports and zero tariffs on new clothing imported from China. Other producer countries, including Bangladesh, China, and Vietnam, some of the largest textile exporters to Europe, have bans on used clothing imports. Intended to protect domestic industry and prevent the dumping of imported waste, these policies are necessary under current trade rules. However, bans can act as barriers to CT.

While some participants advocated that the first sortation of PCT should ideally take place in donor countries, three participants were concerned that proposals to sort, grade, and recycle clothing in Europe would lead to a collapse of collection businesses. Participants agreed that the free movement of specific classes of used apparel for reuse or as feedstock for new materials is essential to the circular economy while emphasising the importance of a robust trade and regulatory framework for accountability, facilitated by digital traceability and better data. Trading used apparel is important for extending the lifespan of clothing and the economic viability of existing collection and sorting businesses in Europe.

All participants involved in trading PCT spoke of a sector where deplorable practices are rife, and transparency is lacking. P1 described the global trade in used textiles as a grey market with connections to organised crime, largely driven by cash, with money laundering being commonplace. These problems begin in donor countries if there is no requirement to have a license to collect textiles.

4.4.2. Enablers

The interviews provided insight into how regulation and trade rules, as well as CT initiatives, could enable T-T recycling.

Three participants noted that compulsory licensing of PCT collectors is necessary to legitimise the sector, citing the licensing of scrap metal collection in the UK as an example of good practice. Four participants called for a revision of HS classifications to allow for more specific product classes within PCT. WTO rules and tariffs could also helpfully differentiate between sorted PCT exported for resale, versus shipments bound for specific locations with sorting and recycling infrastructure.

Achieving critical volumes of specific fibres for recycling, or consistent resale grades requires aggregation of containers of PCT. For example, P2 and P8's global businesses collect PCT in the West and then ship bales to India and Pakistan for manual sorting within their own or third-party operations. Resale grades are exported to appropriate markets, and low-value textiles are shipped to Europe for recycling or sold for downcycling on the local market.

P2 referred to an informal industry comprised of "a very established community and network and an ecosystem of up-cyclers, re-manufacturers, re-users and re-wearers in India and in Pakistan". Trade in used clothing is economically essential in some countries. All participants

stressed the importance of working with informal economies towards a just transition to a CE for textiles.

P17 believes scaling T-T recycling will require leveraging existing capacities and material flows. To achieve this, he proposes situating *mass regeneration zones* in producer countries. These industrial complexes would incorporate sortation, repairs, fibre-to-fibre recycling, textiles production and vertical manufacturing. This approach would provide a circular solution for imported and local PCT, generating economic benefits, and creating a market for low-value textiles to compete with downcycling and prevent dumping. Funding from Europe's Extended Producer Responsibility schemes and production commitments from brands and retailers would attract further investment.

Several participants mentioned that Digital Product Passports (DPPs) would make traceability applicable to PCT in the near future. Enhanced traceability could prevent grey trade and facilitate accountability throughout the value chain. P9 noted that the only constraining factor is the unwillingness of brands and retailers to share data, given that interoperability between traceability systems exists.

4.5. Increasing collection and sortation

In line with the literature, participants agreed that citizens' behaviour change is integral to increasing PCT collection. However, this must be supported by vastly improved infrastructure. Brands also have a role in taking a participative approach to customer relationship management.

4.5.1. Barriers

Three main barriers were identified: A lack of convenient ways to donate, poor collection and sortation infrastructure, and mixed public messaging leading to confusion about textiles recycling.

The absence of national collection strategies has led to a lack of convenient ways to donate all unwanted textiles. Some facilities require a car to access them, many are inconvenient on foot. "We have to really be collecting everything and making it the easiest possible way for the citizens to do so. Does that mean charities increase collection of items that are not wearable? Yes." (P12).

Financial dynamics are the main reason collection rates have not yet increased significantly. Municipalities charge collectors a fee to operate bring-banks which has created a competitive bidding environment in larger cities, driving the kilo price down, while costs increase. Theft from bring-banks is commonplace, and the perception that they are garbage bins leads to contamination (P1). "The problem with the street collection is the downward strand of the quality and the relatively high cost of the collection in terms of labour and equipment". "The logistic costs are roughly the same or even higher than the product cost you have inside" (P8).

The greatest barrier to increasing sorting capacity is a lack of investment in infrastructure and technology for automated sorting and removal of disruptors. Textile sorters cannot fund this because their margins are too low. Therefore, there are few businesses in Europe that can sort and prepare PCTs to the specifications of textile recyclers (P8). A further challenge is that the current technology has a ca. 5 % error rate in identifying fibre compositions, which many recyclers cannot accommodate.

Citizens are receiving mixed messages about textiles recycling, which results in the disposal of PCT into mixed domestic waste. The communication of the charity sector is often that they want items in good condition. There is an absence of messaging regarding how to dispose of low-value textiles (P1, 13, 12).

4.5.2. Enablers

Three participants identified a need for a greater choice of collection modes. Donating to charities is preferred by many citizens, and grocery stores are convenient locations for bring-banks. Alternative collection models are being piloted, for example, Copenhagen has citizens separating re-wearable and non-wearable donations. In P17's experience, kerbside collections attract frequently contaminated low-value PCT. However, with the right incentive, a separate kerbside collection would be viable.

In anticipation of new EPR rules, Brands are increasing take-back schemes in partnership with charities or businesses (P12, P15). P8's proposal is for brands to offer e-commerce customers a service to return used apparel with unwanted purchases so that reverse logistics are cost neutral. A caveat is that customer messaging must encourage the return of any grade of unwanted textiles so that they are not merely taking the crème away from other collection modes (P8).

Although the capital and operating expenditure are considerable, all participants thought that automated sortation coupled with digital traceability had the potential to reduce the cost of sorting. Three participants had experience with automated fibre sortation. In 2 examples automated sorting had been heavily subsidised by government grants. P3 stated "only a few large charities have the scale to operate reverse logistics, warehousing, and sorting for fibre if they are financially supported". This suggests there is potential for increased collaboration between charities and other organisations, but additional funding will also be required.

Further innovation is required to automate the removal of disruptors, P10 had funding to find solutions including the use of centrifugal force and P12 is in partnership with various organisations actively trialling different solutions.

Consumer engagement and pressure are powerful change levers (P17). Several participants called for a citizen information campaign. P4 believed the value of retail take-back schemes might be in changing consumer mindset rather than attracting a volume of donations.

5. Recommendations

The research highlighted an emerging business case for T-T recycling if the EU Textiles Strategy (Directorate-General for Environment, 2022) is implemented effectively, but significant challenges remain. To scale T-T recycling and related activities throughout the value chain, an unprecedented level of value chain collaboration is required. The convening power of such coalitions would be in working with regulators to engage in policy creation and implementation and in creating standards. Additionally, facilitating data sharing through trusted third parties and ensuring representation of all stakeholders, with particular attention to producer countries and those countries importing PCT for resale, sortation, or recycling. There are four main barriers which have a negative reinforcing effect. The recommendations that follow are specific to regulators, brands, as well as collectors, sorters, and T-T recyclers. Recommendations for citizens are captured within these and summarized in Fig. 3.

However, the research established four key, interconnected enablers for scaling T-T recycling that serves as the basis for stakeholder-specific recommendations for action:

1. ***Targeted, enabling regulation*:** only by creating a level playing field through successfully implementing critical regulation including EPR schemes, DPPs, mandated recycled content, and licencing of collectors and exporters will ensure the economic viability of a T-T recycling at scale. Looking at other industries where similar regulations are in place such as electronics and plastics, there is proof that such changes can be achieved.
2. ***Leveraging existing processes and material flows*:** CT and technology transfer could successfully support a just CE transition by leveraging existing global material flows and producer capacities.
3. ***Establish multi-stakeholder initiatives and partnerships*:** There is a strong need for global cross-sector partnerships to effect systemic change. These coalitions should include representatives of businesses and communities in producer countries as well as in Europe and

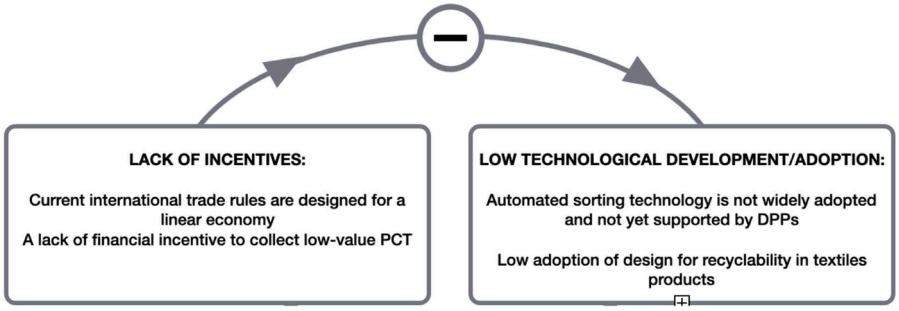

Fig. 3. Interconnected barriers for scaling T-T recycling.

would serve numerous functions: facilitate the aggregation of PCT for recycling, facilitate knowledge transfer, risk sharing (e.g. for pilot schemes), and data sharing, facilitate industrial symbioses, and importantly to match supply and demand at every stage of the circular value chain. Additionally, partnerships can also be a platform to engage traditional venture capital firms, government-sponsored funds (such as Horizon and EPR funds), philanthropies etc., to enhance their industry knowledge and support access to a wider higher-risk capital pool to scale recycling technologies. The multi-stakeholder platforms should proactively organise forums for the broader finance community (venture capital firms, banks, asset managers, pension funds, private equity firms etc.) to engage with actors in T-T recycling and share the importance of technological and infrastructure development. Some great examples already exist, such as Fashion for Good.

4. ***Technology*:** Digital technology has an important role to play in providing necessary end-to-end transparency of product flows and environmental and social product performance (e.g., through DPPs). Further technological innovation is needed to address automated sortation and disruptor removal while leveraging established T-T recycling technologies.

5.1. For regulators

The EU Textiles Strategy is a strong regulatory framework. However, the implementation must be consistent and engage all value chain actors both in and outside of Europe. The authors recommend the following core requirements as part of the legislative process:

- Internalise the cost of PCT by mandating minimum recycled content in new textile products and accounting for externalities in the costs of virgin fibres. This will create a viable market for T-T recycling and should be expedited (12–24 months).
- Financially incentivise T-T recycling through preferential taxation or subsidisation of key activities such as the collection of low-value PCT, and the use of recycled fibres.
- Substantially fund early-stage research to advance recycling and disruptor removal technologies.
- Support CT by adjusting global trade rules, avoiding unintended consequences such as job losses in producer countries or PCT dumping. Ensure legitimacy and transparency of the collection and sorting sector.
- Mandate the use of digital technology for global material traceability, creating full supply chain transparency of material flows and the ability to verify materials content.
- As part of the new sustainability due diligence frameworks (e.g., the EU CSDD Directive, revisions of forced labour acts, etc.), ensure brands and mills are required to take proactive and transparent action to mitigate human rights risks within circular value chain.
- Educate citizens via information campaigning concerted with all stakeholders. Encourage responsible consumption and create a compelling message as to why the era of fast fashion must come to an end.

5.2. For brands

Brands play a central role in scaling the system for T-T recycling. Imminent regulatory requirements will accelerate brands' action in coordination with their supply chains. The following actions are required:

- Make public targets for recycled fibre contents in new products, ramping these up year after year. Delivery will require concerted internal communication, management, and process alignment across all internal functions.
- Create a multi-year product strategy integrating design for T-T recyclability.
- Implement supply chain transparency programs adapted for a circular value chain.
- Make commitments to buy innovative recycled fibres in support of commercialisation. This creates investor confidence and reduces the cost of supply chain capital.
- Establish cross-industry working groups specific to T-T recycling.
- Partner with mills, recyclers, and manufacturers to create *mass regeneration zones* in producer countries integrating T-T recycling with production. If well supported both locally and internationally, this would protect jobs and developing economies.
- Offer customers a choice of in-store and e-commerce take-back schemes. Encourage the donation of all grades of PCT. Drive citizen behaviour change through consistent and compelling marketing beyond the mere uptake of internal take-back schemes.

5.3. For collectors, sorters, and recyclers

Collectors, sorters, and recyclers are the key enablers for operationalising recycling infrastructure but depend on regulators and the brands' actions to create demand for recycled textiles and enabling conditions. Collection, sortation, and recycling technologies are being further developed at a pace. The authors' recommendations for this vital stakeholder group focus on enhancing the economic viability of scaling infrastructure and technology, as follows:

- Use the convening power of industry bodies (e.g., Textiles Recycling Associations) to advocate for funds to leverage established collection models to increase volumes of all grades of PCT.
- Offer citizens a choice of convenient donation modes, including curb side collection and test new modes, such as e-commerce returns.
- Further develop technologies for recycling blends or fibre compositions currently difficult to separate or recycle, such as elastane, nylon and acrylic.
- Make use of new funding opportunities from green finance investors, which are expected to increase in the context of EU Green Deal implementation.

- Transfer recycling technologies to producer counties. Vertically integrate T-T recycling, with textiles and garment production in producer countries via license agreements or business partnerships.

6. Conclusions

While existing literature provides valuable insights into the potential of CE practices in the textile industry, there is a discernible gap in focused research on T-T recycling. Sandvik and Stubbs (2019) identified specific barriers and enablers within the T-T recycling systems in Scandinavia. However, to further advance the understanding and address the limitations of the earlier studies, it is crucial to consider representation of all key stakeholder groups (Piribauer and Bartl, 2019). This research aimed to bridge this gap in the literature by adopting a practitioner perspective, probing the essential question: 'What enabling conditions, infrastructure, and incentives are required to scale a closed-loop system for the recycling of post-consumer textiles?' A review of existing literature paved the way for targeted semi-structured interviews with industry professionals. Practitioners from each stage of the circular value chain were interviewed to consider additional dimensions and factors that could influence the effectiveness of T-T recycling systems. The analysis has identified five overarching themes, each shedding light on the barriers and enablers to the scaling of a closed-loop system for PCT recycling within a European context. Europe was the focus of the study due to incoming legislation that supports a circular textiles system (Kirchherr et al., 2018). The discussion has provided a comprehensive understanding of the challenges and opportunities inherent in the pursuit of a circular economy for textiles.

The first theme underscores the importance of establishing compelling business cases for collecting and sorting low-value textiles, as well as the development and implementation of new textile recycling technologies. The interviews have highlighted the business case for increasing capacity for T-T recycling and related infrastructure, emphasizing the need to reduce barriers and enable businesses to drive profit and attract investment (Kirchherr et al., 2018). The second theme emphasizes the importance of regulation as a crucial enabler of a CE for textiles. The interviewees have articulated specific requests aligned with a collaborative approach in implementing the EU Textiles Strategy (Directorate-General for Environment, 2022), addressing concerns about the specificity of regulations, and presenting a comprehensive overview of stakeholders' perspectives on policy implementation within the EU Strategy for Textiles framework.

The third theme has identified barriers such as product design limitations, consumer expectations (Jäämaa and Kaipia 2022) and corporate culture, while also highlighting enablers such as technological advances, supply chain transparency, and materials traceability (Cura et al., 2022). The interviews have shed light on the challenges and opportunities associated with implementing circular design principles in a commercial environment. The fourth theme has underscored the importance of collaboration across a global system (McCauley and Jestratijevic, 2023) and has identified barriers related to international trade rules, poor sorting practices, and poor accountability throughout the value chain (Sandvik and Stubbs, 2019). The interviews have provided insights into how regulation and trade rules, as well as circular textile initiatives, could enable T-T recycling. The fifth theme has highlighted barriers such as a lack of convenient ways to donate, poor collection and sortation infrastructure, and mixed public messaging leading to confusion about textiles recycling (Hartley et al., 2022). The interviews have also identified enablers such as a greater choice of collection modes, increased take-back schemes by brands, and the potential for automated sortation to reduce costs.

The recommendations focused on four interconnected enablers essential for scaling T-T recycling, serving as the foundation for stakeholder-specific recommendations. Firstly, targeted and enabling regulation is pivotal, emphasizing the importance of successful implementation of critical regulations, including EPR schemes, DPPs, mandated recycled content, and the licensing of collectors and exporters. Leveraging existing processes and material flows is the second enabler, emphasizing the potential of CE and technology transfer to support a just transition. The third enabler highlights the need for multi-stakeholder initiatives and partnerships, involving global cross-sector collaborations to facilitate aggregation of PCT for recycling, knowledge transfer, risk-sharing, and industrial symbioses. Lastly, technology plays a crucial role, with digital innovation needed for transparency, automated sortation, and disruptor removal while building upon established T-T recycling technologies. These enablers provide a strategic roadmap for stakeholders to overcome barriers and drive meaningful advancements in T-T recycling.

In advancing the implementation of recommendations for a just transition to a CE in the fashion and textiles industry, there exist areas of complementary research that could enhance these efforts. Firstly, regarding EPR funding, it should establish a foundation for financing a just transition throughout the PCT value chain (BCG, 2020). Given the nascent nature of EPR for textiles, further research is necessary to ensure that the generated funding is effectively utilized. Another critical aspect is the protection of human rights throughout the PCT value chain, which warrants additional research (Purvis et al., 2023). A considerable portion of the sector operates informally and lacks regulation. This lack of transparency exacerbates human rights risks, already a significant and persistent concern in the textiles sector (Cura et al., 2022). Furthermore, there is a clear need for Multi-Stakeholder Initiatives (MSIs) and partnerships to align supply and demand. However, the specific forms these collaborations should take necessitate further investigation. Lastly, gaining insights from an analysis of relevant case studies where attempts have been made to scale T-T recycling would contribute valuable perspectives to inform future research.

In conclusion, the research findings provide a comprehensive understanding of the enabling conditions, infrastructure, and incentives required to scale a closed-loop system for the recycling of post-consumer textiles. The identified themes and insights offer valuable guidance for policymakers, industry stakeholders, and researchers seeking to advance the CE for textiles. The findings underscore the need for collaborative efforts, regulatory frameworks, technological innovation, and consumer engagement to overcome barriers and drive meaningful advancements in textiles recycling (Fig. 4).

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CRediT authorship contribution statement

Fiona Charnley: Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing. **Ruth Cherrington:** Writing – review & editing. **Florian Mueller:** Investigation, Validation, Writing – original draft. **Ajay Jain:** Investigation, Validation, Writing – original draft. **Cherie Nelson:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Saskia Wendland:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Sonia Ventosa:** Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

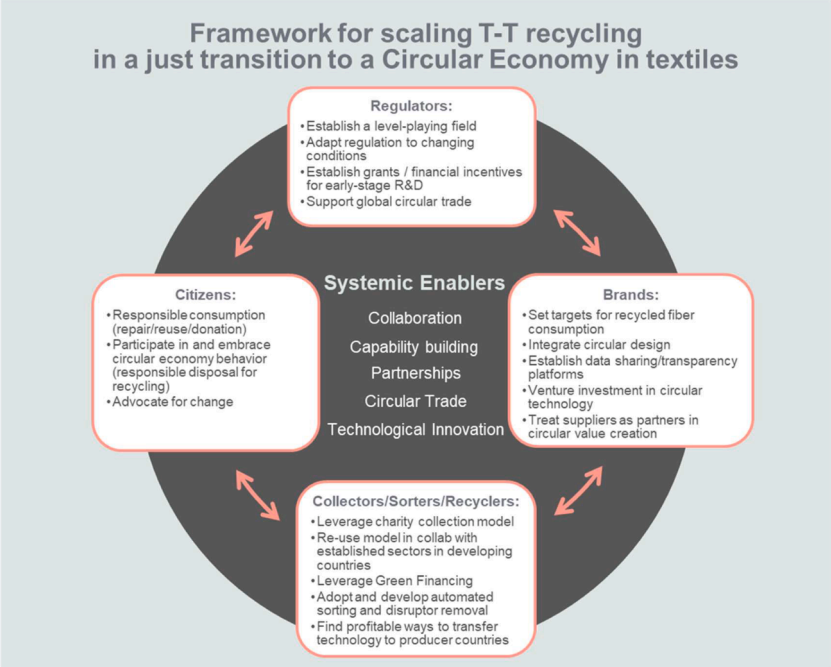

Fig. 4. Framework for scaling T-T recycling.
Note: Summary of key recommendations. Full details are provided in the recommendations.

Data availability

Data will be made available on request.

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Appendix A. Key extant literature

Scope	Authors date	Publication
Textile recycling methods	Wang et al., 2022	Recycling of Waste Cotton Textile Containing Elastane Fibers through Dissolution and Regeneration. Membranes, 12(4). https://doi.org/10.3390/membranes12040355
	Li et al., 2019	Recovery of Glucose and Polyester from Textile Waste by Enzymatic Hydrolysis. Waste and Biomass Valorization, 10(12), 3763–3772. https://doi.org/10.1007/S12649–018–0483–7
	Akı et al., 2020	Understanding Denim Recycling: A Quantitative Study with Lifecycle Assessment Methodology. www.intechopen.com
	Youjiang, 2006	Recycling in Textiles: A volume in Woodhead Publishing Series in Textiles. Woodhead Publishing.
	Ammar et al., n.d	Small Change, Big Impact: A Comparative Life Cycle Assessment of Disassembly & Recycling Methods in Closed-Loop Denim Production. https://doi.org/10.1016/j.jclepro.2016.12.048
The business case for textiles-to-textiles recycling	WRAP, 2019	Fibre to fibre recycling: An economic & financial sustainability assessment. www.wrap.org.uk
	Kirchherr et al., 2018	Barriers to the Circular Economy: Evidence From the European Union (EU). Ecological Economics, 150, 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028
	Henry et al., 2019	A Typology of circular start-ups: An Analysis of 128 circular business models. https://doi.org/10.1016/j.jclepro.2019.118528
Circular supply chain and reverse logistics	Majumdar et al., 2022	A triple helix framework for strategy development in circular textile and clothing supply chain: an Indian perspective. Journal of Cleaner Production, 367, 132954. https://doi.org/10.1016/j.jclepro.2022.132954
	Pal et al., 2019	Making Resilient Decisions for Sustainable Circularity of Fashion Introduction and Background: the Need for Resilient Decision-Making for Sustainable Circularity. Circular Economy and Sustainability. https://doi.org/10.1007/s43615-021-00040-1
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Scope	Authors date	Publication
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Appendix B. Scaled T-T recyclers

RECYCLING METHOD	BUSINESS	LOCATION	PCT FEEDSTOCK	OUTPUTS
Chemical	Ervnu	USA	Cellulosics	NuCycl™ Lyocell fibre
	Re:newcell	Sweden	Cellulosics	Circulose® pulp cellulose
	HeiQ and Renewcell partnership	Switzerland	Cellulosics	High tenacity cellulosic filament yarns
	Lenzing	Austria	Cellulosics	Tencel x Refibra lyocell fibres
	Södra / Once More	Sweden	Blended cellulosic textiles and wood	OnceMore® dissolving cellulosic pulp
	Infinited Fiber Company	Finland	Cotton / Cellulosic fibres / Cellulosic fibre blends	Infinna™ MMCF
	Spinnova	Finland	Paper pulp / Cellulose biomasses	Cellulosic filament fibre
	Blocktexx	Australia	Polyester / Cotton textiles	rPET pallets / cellulose powder
	Ambercycle	USA	Polyester	Cycora® polyester yarns
	Worn Again	United Kingdom	Wood / Polyester / Cotton	Polyester and MMCF blend yarn
	Itochu Corp, Tejin Limited, JCG Holdigs Corp	Japan	Polyester	RENU polyester yarns
Thermo-chemical	CuRe Technology	Netherlands	Polyester and PET	Transparent PET granulate suitable for textiles and consumer goods
Mechanical / Chemical	Circ and Andritz parternship	USA / Austria	Cotton / Polyester / Polycotton blends	MMCF
Mechanical	Crescent Bahuman	Pakistan	Denim	Denims
	Naveena Mills	Pakistan	Denim	Denims
	Osmotex®	USA	Mixed fibres	Osom brand yarns
	Kipas Textiles	Turkey	Cotton	RCO100 recycled cotton denims
	Santis Textiles	Switzerland	Cotton	RCO100 recycled cotton fibres
	Bossa	Turkey	Cotton	Denim fabrics with recycled PCT content
	Artistic Denim Mills Ltd	Pakistan	Cotton	Denim fabrics with recycled PCT content
	Recover & Sysav	Spain	Cotton	ReFab® cotton fibres

Appendix C. - Interview protocol with example questions

The interview protocol designed to engage with practitioners to gain a perspective on scaling a closed-loop system for the recycling of post-consumer textiles and encompasses various crucial areas. The questions are structured to gather information regarding business details, scaling intentions, waste sorting processes, logistics, partnerships, regulation, and the impact of design on recycling. The protocol aims to elicit detailed insights from practitioners involved in the textile recycling industry. They aim provide a balance between structure and flexibility, allowing for the exploration of specific topics while providing the freedom to pursue unanticipated avenues of inquiry.

Section 1. Business information

This section seeks to gather foundational details about the practitioners' enterprises, including their business name, founding date, location, annual turnover, profitability, ownership structure, number of employees, and existing financing arrangements. This information is crucial in understanding the current state of the businesses involved in textile recycling and their financial and operational capacities. Questions include:

- When was the business founded and where is it located?
- What is the annual turnover of the business in Euros?
- Is the current business profitable? If yes, for how many years?
- What is the ownership structure of the business?
- How many employees does the business have?
- Are there any financing arrangements in place?

Section 2. Scaling

This section delves into the practitioners' growth intentions, financial requirements, funding mechanisms, barriers, and enablers to growth. Understanding their growth plans and financial needs is essential for assessing the potential for scaling a closed-loop system for textile recycling and identifying the challenges they may encounter in the process. Questions include:

- Is the business intending to grow in the next 5 years?
- Is additional finance required to support that growth?
- What funding mechanisms would provide additional finance and are they readily accessible?
- What challenges do you foresee in raising additional funding?
- Are there any additional barriers or enablers to growth?

Section 3. Sorting waste, material flows, and logistics

This section focuses on the volume of textiles sorted, pricing, re-making, or repairing of textiles, waste disposal, and logistics. This information is vital for understanding the current waste management processes, the volume of textiles involved, and the existing challenges in waste disposal and recycling. It also aims to uncover the methods used for sorting textiles, identification of fibre composition, and the potential to facilitate ease of sourcing and reduce waste. This insight is crucial for evaluating the current sorting processes and identifying opportunities for improvement. Questions include:

- How many tonnes of textiles do you sort per annum?
- Do you pay for incoming (textiles) and if so, what is the Euro kilo price?
- Where do the used clothing/textile you sort originate from?
- What process do you use to sort the incoming textiles? Do you identify the fibre composition?
- What aspects of design would most facilitate ease of sorting?

Section 4. Partnerships and regulation

This section seeks to understand the existing business partnerships, regulatory requirements, and industry affiliations that may impact the scaling of a closed-loop system for textile recycling. This information is essential for assessing the collaborative networks and regulatory landscape influencing the industry. Questions include:

- Do you have any business partnerships that are integral to your business model?
- From your perspective, what changes to regulation would support scaling a closed loop system for textiles?
- Are you a member of any industry bodies or organisation that have the aim of scaling a closed loop system for textiles?

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