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ECO-CIRCULAR DENIM: A SYSTEMATIC LITERATURE REVIEW ON THE ECO-SUTAINABLE AND CIRCULAR URBAN MODEL

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Abstract

The growing environmental and climate crises require a fundamental transformation of production, consumption and waste management systems. Textiles are a critical sector. Denim is one of the most widely used and resource-intensive fabrics. Its reliance on cotton, chemical-heavy finishing processes and substantial post-consumer waste exemplifies the challenges posed by fast fashion. This paper conducts a systematic literature review to explore the application of circular economy principles within the denim sector. The findings reveal four interconnected themes: Environmental impacts, which highlight the ecological burden of denim production and the potential benefits of fibre-to-fibre recycling; Supply chain and municipal roles, which emphasise the importance of local infrastructure and governance in facilitating textile recovery; Circular practices and consumer behaviour, which show the opportunities and challenges of bridging the gap between attitudes and behaviours regarding circular practices; Regulatory and policy frameworks, which underline the enabling role of European strategies such as the Green Deal, the Circular Economy Action Plan, the Eco-design for Sustainable Products Regulation and the Waste Framework Directive. Building on these insights, the paper introduces the Eco-Circular Denim model: a smart, municipality-centred framework integrating eco-design, digital traceability, consumer engagement and extended producer responsibility in post-consumer denim management. This positions the model as a strategic entry point for operationalising the circular economy in urban contexts, aligning local infrastructure with EU policy ambitions. By connecting technological innovation, behavioural changes and governance mechanisms, the study offers a comprehensive approach to reducing environmental impact, enhancing resource efficiency and promoting circular urban textile systems.

Key words: circular economy, denim waste management, digital technologies, regulatory frameworks, sustainable fashion, municipal governance

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1. Introduction

The growing environmental crisis, resource depletion and climate instability have created an urgent need for a global shift from linear production models, characterized by a "take-make-dispose" approach, to sustainable and regenerative practices (Mosconi et al., 2024). The textile and apparel industry has been central to discussions about sustainability due to its substantial consumption of natural resources, high energy usage and significant contribution to waste generation (Tarantino et al., 2023). Globally, textiles account for approximately 10% of greenhouse gas emissions and 20% of industrial wastewater, making this sector one of the most environmentally harmful (Shirvanimoghaddam et al., 2020). The industry is primarily driven by a linear "fast fashion" model, where garments are quickly designed, produced and discarded, often within a single season (Gunavarthani and Princy, 2025; Niinimäki and Durrani, 2021). This model has led to a doubling of clothing production over the past two decades, with more than 100 to 150 billion garments introduced to the market annually, resulting in about 92 million tonnes of textile waste each year (Shamsuzzaman et al., 2025). One defining feature of

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the fast fashion industry is the short lifespan of garments (Kalambura et al., 2020). More than half of fast fashion items are discarded within a year of purchase, leading to premature disposal and limited opportunities for reuse or recycling (Niinimäki and Durrani, 2021). The growing influence of e-commerce and influencer-driven marketing has further reinforced consumer demand for novelty, intensifying unsustainable consumption patterns (Papamichael et al., 2023). These dynamics increase the burden on municipal solid waste (MSW) systems, where textiles often enter mixed waste streams, making recovery and recycling more difficult (Sarker et al., 2024; Sharkey and Coggins, 2022). Within this broader context, denim plays a particularly critical role (Zhao et al., 2021). It is one of the most ubiquitous and resource-intensive textiles, with global production estimated to be between 3 and 4 billion pairs of jeans per year, valued at approximately USD 90 to 107 billion (Huang et al., 2025). Jeans, the main application of denim, have become a ubiquitous item of clothing globally and a symbol of fast fashion consumption.

The environmental footprint of denim is shaped by several factors. Cotton cultivation, which accounts for nearly 10% of the world's cotton production (around 2.5 million tonnes annually), requires extensive irrigation and pesticide use (Hossain and Rahman, 2025; Asmi et al., 2022). Additionally, the dyeing and finishing processes involve hazardous chemicals such as indigo, bleaching agents and resins, while post-production phases like stone washing or sandblasting further increase resource intensity (Periyasamy and Periyasami, 2023; Eroglu, 2023; Zhao et al., 2021). At the consumer stage, laundering contributes to the release of synthetic microfibers, which have been detected in rivers, lakes, and marine ecosystems, raising concerns about aquatic toxicity and accumulation in the food chain (Sharma et al., 2024). Denim waste accounts for nearly 5% of landfill volume, highlighting its disproportionate impact compared to other textile categories (Huang et al., 2025). However, denim's material properties, primarily its cotton composition, durability and relative design uniformity, make it a suitable candidate for circular interventions (Asmi et al., 2022). Fibre-to-fibre recycling has shown potential to replace more than 70% of virgin cotton if at least 80% of pre- and post-consumer denim waste is collected and reprocessed (Gachenga, 2022). Life cycle assessments (LCAs) indicate that using 100% recycled cotton in denim production can reduce water consumption by 98% and greenhouse gas emissions by 54% compared to virgin cotton (Zhao et al., 2021). Despite these advantages, the literature identifies ongoing barriers to achieving denim circularity (Uncu Aki et al., 2021; Uncu Aki et al., 2020). From a technical perspective, blended fabrics, such as cotton–polyester and cotton–elastane, hinder efficient fibre separation and degrade the quality of recycled outputs (Jugend et al., 2024; van Raan, 2019). Systemically, fragmented collection infrastructures, inconsistent sorting practices and limited investment in recycling facilities impede scaling efforts (Barletta et al., 2024; Shirvanimoghaddam et al., 2020). Behaviourally, consumers often associate recycled textiles with reduced quality, hygiene issues or diminished social value, which limits the acceptance of recycled denim products (Hugo et al., 2021; Vehmas et al., 2018). This results in a significant attitude behaviour gap: while consumers express concern for sustainability, their actual purchasing practices frequently prioritize low cost and trendiness over durability and recyclability (Papamichael et al., 2023). Emerging research points to several opportunities for improvement. New business models, including clothing leasing, rental, resale and upcycling, challenge the fast fashion paradigm by extending product lifecycles and creating new revenue streams for companies (Barletta et al., 2024). Traditional practices of textile reuse and repair, along with innovative approaches such as upcycling aquaculture waste into functional textiles (Manian et al., 2022; Nayak et al., 2022), suggest cross-sectoral strategies for material valorisation. Additionally, biotechnological innovations, such as bacterial cellulose derived from kombucha fermentation, are being explored as sustainable alternatives to cotton in denim production (Provin et al., 2021). At the governance level, the European Union has made textiles a central focus of its sustainability agenda. The European Green Deal (EC, 2019) sets an overarching goal for climate neutrality by 2050. The New Circular Economy Action Plan (EC, 2020), known as "CEAP 2.0", and the EU Strategy for Sustainable and Circular Textiles (EC, 2022) mandate that by 2030, all textile products sold in the EU must be durable, repairable and recyclable. Furthermore, the amended Waste Framework Directive (EU Directive, 2018) requires the separate collection of textile products by 2025. The Eco-design for Sustainable Products Regulation (EU Regulation, 2024) and the Directive on repair of goods (EU Directive, 2024) further emphasize the need for durability, reusability and circularity. These policy measures highlight the growing significance of municipal systems as key players in textile waste governance. Despite recent advances, the academic literature on textile circularity remains fragmented. Various studies have explored specific dimensions of this topic:

1. Environmental impacts and recycling potential: Research has focused on denim, examining aspects such as fibre-to-fibre recycling and the use of regenerated cellulose fibres (Huang et al., 2025; Koszewska, 2018).

2. Consumer behaviour and perceptions: Studies highlight the persistent gap between attitudes and behaviours, as well as the stigma associated with recycled textiles (Niinimäki and Durrani, 2021; Papamichael et al., 2023; Vehmas et al., 2018).

3. Business models: Innovative approaches such as leasing, product-service systems (PSS), rental and upcycling are identified as pathways toward sustainable consumption (Barletta et al., 2024; Sharma et al., 2024).

4. Digital enablers: Technologies such as

blockchain for supply chain transparency, the Internet of Things (IoT) for real-time tracking, artificial intelligence (AI) for sorting and process optimization and Digital Product Passports (DPPs) are emerging as tools that empower consumers and facilitate cross-border material circulation (Alves et al., 2022).

However, a systematic synthesis that integrates these diverse perspectives to explore how circular economy practices can be implemented at a municipal level is notably absent, particularly regarding denim as a significant material. Most existing studies focus narrowly on environmental science, consumer behaviour, business innovation or digital technologies, failing to provide a comprehensive framework connecting the technical, behavioural, systemic and governance dimensions. Furthermore, the crucial role of municipalities in implementing CE principles, as required by EU legislation, has not been adequately addressed in academic discussions. This paper addresses this gap by conducting a systematic literature review (SLR) of circular economy strategies in the fashion and textile sector, with a specific focus on denim. The review investigates environmental, technical, behavioural and systemic barriers to achieving circularity; the enabling role of digital technologies; and governance models relevant to MSW systems.

The review is guided by the following questions:

RQ1: What are the main environmental challenges associated with denim throughout its lifecycle, and how can circular strategies such as eco-design, reuse, repair, and fibre-to-fibre recycling help mitigate resource consumption and pollution?

RQ2: How do supply chain actors and municipal waste management systems contribute to advancing circularity in the denim industry, and what infrastructural or organizational barriers limit their effectiveness?

RQ3: What factors influence consumer acceptance and adoption of circular practices in the denim sector, and how can innovative business models, such as reuse, repair, leasing, upcycling, help reduce the attitude, behaviour gap in sustainable fashion consumption?

RQ4: How do European and international policy frameworks, such as the EU Green Deal, the Circular Economy Action Plan, the Waste Framework Directive and the Eco-design for Sustainable Products Regulation, shape the governance of circular textile systems? Additionally, what role can municipalities play in translating these policies into actionable strategies?

2. Material and methods

This study employs the PSALSAR methodology (Mengist et al., 2020) to ensure the transparency, replicability, and analytical depth of the systematic literature review (SLR). The PSALSAR framework consists of six sequential steps:

(i) Protocol, which defines the purpose of the study;
(ii) Search, which determines the strategy for retrieving relevant publications;
(iii) Appraisal, which establishes inclusion and exclusion criteria to select relevant studies;
(iv) Synthesis, which involves cataloguing and organising the selected studies;
(v) Analysis, which extracts and interprets findings from the literature;
(vi) Report, which presents the results and conclusions of the SLR in a clear and structured way.

This paper discusses steps (i) to (iv) in the present section, while step (v) is developed in Section 3 (Results) and step (vi) in Sections 4 and 5 (Discussion and Conclusions).

The purpose of this SLR is to synthesise academic and policy-oriented literature on circular economy (CE) practices in the textile and fashion sector, with a particular focus on post-consumer denim waste. The study seeks to identify the environmental impacts, barriers, enabling conditions, and governance models that can inform the development of a smart, participatory municipal framework for denim circularity. To operationalise this objective, the CIMO framework was employed to structure the review (Table 1).

This method shifts the review from simply mapping literature to linking interventions and mechanisms with contextual challenges and intended sustainability outcomes. The literature search was conducted from January to July 2025 across two major databases: Scopus and ScienceDirect. These databases were selected for their extensive coverage of environmental, management, engineering and social sciences.

Table 1. Study protocol definition using the CIMO methodology

Context	The global textile and fashion industry, with emphasis on denim as a critical material stream, within the broader European policy framework (e.g. EU Green Deal, CEAP 2.0, EU Strategy for Sustainable and Circular Textiles, Waste Framework Directive).
Input	Adoption of CE strategies such as reuse, repair, recycling, upcycling, and innovative business models, supported by digital technologies (IoT, blockchain, AI, Digital Product Passports).
Mechanism	Processes and enabling conditions that enhance consumer engagement, improve material traceability, strengthen municipal solid waste (MSW) systems, and foster multi-stakeholder collaboration.
Outcome	Identification of the main barriers, drivers, and enabling conditions for advancing circular economy practices in denim and textiles, with particular attention to the role of municipalities and digital technologies in supporting scalable and participatory approaches to post-consumer textile waste management.

The search employed various combinations of keywords related to textiles, denim and the circular economy. Boolean operators (AND, OR) and truncations were used to enhance the retrieval process. Examples of effective search strings included:

- "circular economy" AND "textile" OR "fashion"
- "circular economy" AND "denim" OR "jeans"
- "post-consumer textile waste" AND "circularity"
- "recycling" OR "reuse" OR "repair" AND "denim"
- "smart city" OR "municipal waste" AND "circular fashion"
- "blockchain" OR "IoT" OR "artificial intelligence" AND "textile industry"

This comprehensive approach resulted in the identification of 1.188 potentially relevant documents for the literature review. Once the documents were collected, they were accompanied by relevant information and corresponding abstracts. To streamline the screening and eligibility determination process, these files were uploaded to the Rayyan platform, following the methodology outlined by (Pellegrini and Marsili, 2021). During this phase, eligibility criteria (Table 2) were established to guide the initial inclusion and exclusion of documents. The selection criteria included studies published in the last 10 years, specifically from 2015 to 2025. Only articles published after 2015 were included, as the aim is to study the evolution of scientific research related to the areas of intervention since the introduction of the First Action Plan for the Circular Economy (EC, 2015), known as "CEAP". By applying the eligibility criteria, we were able to move forward to the operational phase of selecting the articles for the Systematic Literature Review (SLR) on the Rayyan platform. This process followed the steps outlined in Fig. 1 of the PRISMA flowchart. The screening process was divided into several stages:

Table 2. Eligibility criteria defined in the Appraisal phase

Eligibility Criteria	***Decision***
The chosen keywords exist at least in the title or abstract section of the document	Inclusion
The document is published in a peer-reviewed scientific journal	Inclusion
The document is written in the English language	Inclusion
Only paper Open access	Inclusion
The paper is duplicated within the search documents	Exclusion
The full paper is not available or accessible	Exclusion
The document is published before 2015	Exclusion

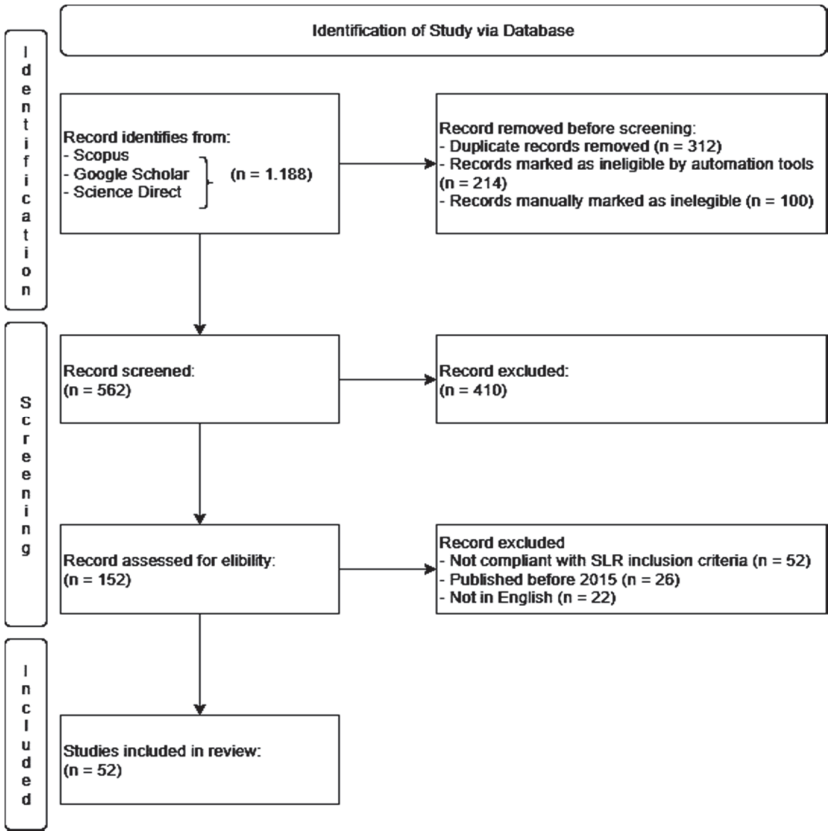

Fig. 1. Prisma Flow Diagram

At the end of the screening process, 52 articles were identified, across Scopus and ScienceDirect, after removing duplicates and ineligible studies. The bibliometric analysis reveals both the temporal evolution and geographical distribution of academic contributions related to denim circularity. As illustrated in Fig. 2, the number of publications was minimal between 2017 and 2019. However, from 2020 onwards, there was a sharp increase. This surge aligns with the European Union's policy, particularly the launch of the European Green Deal (EC, 2019) and the New Circular Economy Action Plan (EC, 2020), both of which explicitly identified textiles as a priority value chain. The temporal trend suggests that regulatory developments at the EU level acted as catalysts for scientific literature, stimulating research on the environmental impacts and governance strategies within the denim sector. The geographical distribution of publications, shown in Fig. 3, further underscores the global nature of denim production and the challenges of waste management. Turkey, China, and India are identified as leading contributors, collectively making up a significant portion of the reviewed literature. This aligns with their roles as major producers within the global textile and denim supply chains. Key contributions from Brazil and South Africa address waste valorisation and the socio-economic impacts of textile recycling, representing the Global South perspective. European countries such as France, Italy, Portugal, Sweden, Austria and Finland primarily focus on regulatory, eco-design and policy-oriented research.

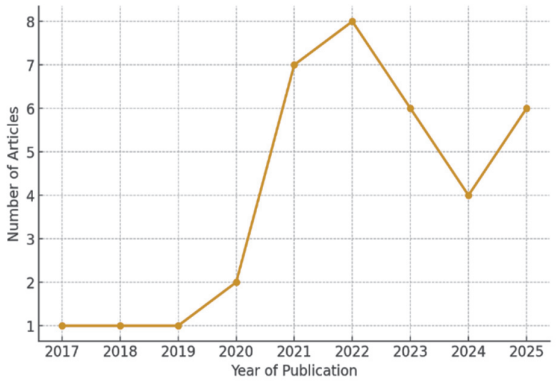

Fig. 2. Distribution of selected articles

Overall, these bibliometric insights reveal how literature is influenced by both the geographies of production (with Turkey, China and India as denim manufacturing hubs) and the regulatory landscapes (with EU countries aligned with the European Green Deal agenda). This interplay highlights the importance of connecting technological innovation in production-intensive countries with governance and regulatory frameworks emerging from Europe. Establishing this connection is essential for operationalizing the Eco-Circular Denim model proposed in this study, as it requires both upstream innovation and downstream regulatory harmonization to be truly effective.

3. Results and discussion

The keyword analysis conducted on the 52 selected articles provided a solid foundation for structuring the results of this systematic review. By extracting the most frequently occurring terms from the keywords, the analysis revealed four distinct but interconnected clusters that reflect the major thematic directions of current research on circularity in the textile sector, particularly concerning denim. The first cluster, "Environmental impacts," is dominated by keywords such as cotton, water footprint, life cycle assessment, dyeing, wastewater, and microfibers. This highlights the resource intensity and ecological burden of denim throughout its lifecycle. The second cluster, "Supply chain and municipal roles," is shaped by terms like collection, sorting, logistics, municipal waste and traceability. This emphasizes the importance of local governance and coordinated infrastructure in ensuring effective post-consumer textile management. The third cluster, "Circular practices and consumer behaviour," revolves around concepts such as reuse, repair, upcycling, clothing leasing, product-as-a-service, consumer behaviour, and sustainability awareness.

This points to the crucial role of societal engagement and innovative business models in extending product lifecycles. Finally, the fourth cluster, "Regulatory and policy frameworks," is characterized by terms such as the European Green Deal, Circular Economy Action Plan (CEAP), Eco-design for Sustainable Products Regulation (ESPR), Extended Producer Responsibility (EPR) and sustainability policies. This reflects the increasing influence of EU policy in guiding systemic change across the textile sector. The overlaps between clusters, particularly around keywords like recycling, digital technologies, and denim, underscore the interconnected nature of environmental, technical, behavioural and regulatory dimensions. This interdependence confirms that the transition towards denim circularity cannot be achieved through isolated interventions; it requires an integrated and multi-scalar framework.

3.1. Environmental impacts of denim waste

The first cluster emerging from the systematic literature review highlights the substantial and multi-faceted environmental impact of denim throughout its entire life cycle. Compared to other textiles, denim exhibits an exceptionally high ecological footprint, beginning with raw material extraction and extending through production, consumer use, and end-of-life management (Amutha, 2017). Denim production is heavily reliant on cotton, a crop that demands intensive inputs of water, land, and agrochemicals.

Fig. 3. Distribution of publications by country

It is estimated that the annual production of 3 to 4 billion pairs of jeans contributes to nearly 10% of global cotton consumption, with the cultivation of cotton accounting for approximately 2.6% of the world's freshwater use and involving extensive application of pesticides and insecticides (Shwetha et al., 2023). Producing a single pair of jeans requires around 2,900 litres of water, and the cumulative environmental pressure is further exacerbated by the massive global scale of production (Koszewska, 2018).

Literature suggests that merely extending the average garment lifespan by three months could reduce carbon emissions, water use and waste generation by up to 10%, underscoring the significance of durability-oriented interventions (Cheng and Liang, 2021). The subsequent industrial phases, especially dyeing and finishing, present additional environmental burdens. Denim's characteristic indigo hue is achieved through synthetic dyeing processes that consume tens of thousands of tonnes of hazardous chemicals, including indigo dye, sodium dithionite and caustic soda (Fidan et al., 2021). These substances generate wastewater with high chemical loads, often containing toxic and potentially carcinogenic compounds. Without adequate treatment infrastructure, the effluents released from denim manufacturing pose severe risks to aquatic ecosystems and human health (Jacometti, 2019). Popular finishing methods such as stonewashing and sandblasting introduce further concerns. Stonewashing relies on abrasive pumice stones that disintegrate during processing, producing sludge and airborne dust, while sandblasting is associated with occupational health risks such as silicosis due to the inhalation of fine silica particles (Provin et al., 2021).

The environmental burden of denim does not cease at the point of sale. Post-consumer impacts, frequently underestimated, play a significant role in the material's lifecycle emissions (Asmi et al., 2022). Laundering jeans leads to the release of microfibres, including both cotton particles and synthetic fragments from elastane blends, which accumulate in freshwater and marine ecosystems (Vehmas et al., 2018). It is estimated that nearly half a million tonnes of microfibres enter the oceans each year from domestic washing, contributing to bioaccumulation and contamination of food chains. Moreover, current disposal patterns are largely linear, with the vast majority of post-consumer textile waste ending up in landfills or incinerators (Rabbi et al., 2023). Natural fibres such as cotton decompose slowly under anaerobic conditions, releasing methane, while synthetic components leach toxic substances into soil and groundwater. Less than 15% of textile waste is currently recycled, and consumer habits, such as discarding jeans after approximately 20 uses, further inflate the volume of waste (Rabbi et al., 2023). The literature estimates that approximately $400 billion worth of garments is wasted annually, signalling both an environmental and economic failure in current fashion systems (Hugo et al., 2023). In response, numerous LCA studies have evaluated the potential of circular approaches, particularly fibre-to-fibre recycling, to mitigate denim's environmental impact. Findings consistently show that if 80% of denim waste, both pre- and post-consumer, were recovered and recycled, over 70% of virgin cotton demand could be offset (Shamsuzzaman et al., 2021). The use of 100% recycled cotton in denim production may reduce water use by up to 98% and greenhouse gas emissions by 54% compared to conventional processes (Kurniawan et al., 2022).

In addition, recycled cotton does not require arable land or irrigation, offering an environmentally superior profile over its virgin counterpart. However, despite this promising outlook, technical barriers remain prevalent. The widespread use of blended fabrics, especially cotton-polyester and cotton-elastane combinations, complicates mechanical recycling processes by reducing fibre quality and limiting the suitability of the output for new garments

(Sondh et al., 2024). Non-textile components such as rivets, leather patches, zippers and thick seams further interfere with efficient material recovery and can damage recycling machinery. Variability in garment colour and composition hinders standardisation and necessitates energy-intensive sorting and re-dyeing processes. While chemical recycling is often proposed as a solution for blended textiles, it presents its own challenges, including toxicity risks, high energy requirements and limited scalability (Nayak et al., 2022). The environmental cost of conventional denim production and disposal is both unsustainable and avoidable, provided that appropriate circular mechanisms are developed and implemented (Noor and Anjum, 2024). These must include upstream measures such as eco-design and material mono-composition, midstream innovations in sorting and pre-processing and downstream investments in scalable fibre recovery technologies. This body of evidence establishes a strong rationale for the development of localised, integrated and digitally enabled models for circular textile management (Cruz and Rosado da Cruz, 2023).

3.2. Roles of the supply chain and municipalities

The second cluster emphasise the crucial role of supply chains and municipalities in facilitating denim circularity. The literature underscores that denim waste management cannot be addressed in isolation but rather requires coordination between different stakeholders, infrastructures and governance levels (Maramura and Ruwanika, 2023). EU municipalities are particularly important because, from 2025, they will be legally responsible for the separate collection of textiles under the Waste Framework Directive, making them central arenas for operationalising CE principles (Schafhäutle, 2023). Efficient supply chains are essential for reducing contamination and increasing recovery rates. Ineffective sorting and fragmented logistics can undermine recycling potential, but digital tools such as AI-based recognition, IoT monitoring and blockchain traceability show promise in enhancing collection and processing efficiency (Zindi and Sibanda, 2022). However, investment and technical capacity remain uneven across regions, creating disparities in system performance (Phahlamohlaka and Mpungose, 2025).

Municipalities are emerging as hubs of collaboration, connecting brands, recyclers, waste operators and citizens (Maramura and Ruwanika, 2023). Successful initiatives depend on public engagement and well-designed local infrastructure, such as dedicated take-back schemes, textile banks and partnerships with social enterprises (Schafhäutle, 2023). Financial and organisational barriers, particularly in smaller municipalities, continue to limit adoption, with the costs of collection and sorting often exceeding the revenues generated from recovered fibres (Zindi and Sibanda, 2022). The relatively standardised fibre composition and design characteristics of denim make it an ideal material for municipal pilot projects (Hossain and Rahman, 2025). In this context, experiences from other public service sectors show that municipalities have the potential to drive systemic innovation through participatory, digital approaches. For example, local governments have successfully co-designed and implemented new policy models in the field of distance and online learning to meet emerging societal needs (Mosconi et al., 2013). These findings highlight the importance of municipal governance as not only an executor of EU mandates, but also a strategic enabler of circular transformation.

However, progress is hindered by weak cross-actor coordination, a lack of harmonised standards, and an absence of extended producer responsibility schemes that could allocate costs fairly across the supply chain (Mgidi and Kholopane, 2023). Therefore, strengthening municipal roles with the support of digital tools and EU-level harmonisation is critical for scaling denim circularity. Similar governance challenges, balancing local waste management capacities with transnational material flows, have been documented in other circular economy sectors, suggesting that municipality-centred frameworks may offer transferable insights across material-intensive industries (Tola et al. 2023).

3.3. Circular practices and consumer behaviour

The third cluster of the literature focuses on the role of circular practices and consumer behaviour in

shaping the transition of the denim industry towards a circular economy. The evidence demonstrates that while technological and regulatory measures are necessary, the active engagement of consumers and the adoption of innovative business models are indispensable for closing material loops. The prevailing fast fashion model fosters frequent purchases and short garment lifespans, reinforcing a culture of disposability that directly fuels post-consumer textile waste (Kalambura et al., 2020; Shamsuzzaman et al., 2021). Jeans are particularly affected by this trend, as studies show that consumers often discard denim after an average of 20 wear cycles, while laundering practices, typically, after every 10 wears, further reduce durability and contribute to microfibre pollution (Sharma et al., 2024). This behaviour illustrates the so-called attitude–behaviour gap, where consumers express environmental concern yet continue unsustainable purchasing and disposal patterns (Koszewska, 2018).

Research also reveals cultural and socio-economic differences in consumer engagement: consumers display higher levels of fast fashion consumption compared to their Croatian counterparts (Kalambura et al., 2020), highlighting the importance of contextual factors in shaping behavioural drivers. Alongside these barriers, literature identifies emerging practices and business models that can foster denim circularity. Initiatives such as reuse, repair, and upcycling have gained visibility in both academic research and industry experimentation. Upcycling of

textile and aquaculture waste, for instance, demonstrates how discarded materials can be transformed into high value products such as functional textiles, insulation and composite materials (Shirvanimoghaddam et al., 2020). At the business model level, clothing rental, leasing, and product-as-a-service are increasingly discussed as strategies to decouple value creation from resource consumption (Alves et al., 2022; Barletta et al., 2024). These models not only extend product lifecycles but also facilitate municipal collection and redistribution, linking consumer participation with local waste management practices.

The literature further emphasises the role of digital technologies in bridging behavioural barriers. Tools such as blockchain and Digital Product Passports can provide transparent information on material composition and provenance, increasing consumer trust in recycled denim and enabling informed purchasing decisions (Cruz and Rosado da Cruz, 2023). Similarly, IoT-enabled platforms and mobile applications can enhance consumer engagement by offering feedback on sustainable behaviour, while nudging strategies, such as eco-labelling, deposit-return schemes or gamified reward systems, have been found to positively influence consumer choices towards sustainable textiles (Falcone and Fiorentino, 2025).

Overall, the literature highlights that consumer behaviour is a critical enabler for denim circularity. While the environmental benefits of recycling and reuse are clear, their realisation depends on consumer willingness to return, repair or purchase circular denim products. Addressing psychological barriers, improving design for durability and embedding digital transparency tools are therefore essential strategies to align consumer practices with circular economy objectives. Within this context, municipalities can play a vital role in activating behavioural change by implementing local collection schemes, awareness campaigns and incentive-based systems.

3.4. Regulatory and policy frameworks

The fourth cluster examines the European regulatory landscape that frames denim circularity and more broadly, textile sustainability. At the strategic level, the European Green Deal sets the overarching objective of climate neutrality by 2050 and anchors resource efficiency and waste prevention as core principles of industrial transformation. Building on this, the New Circular Economy Action Plan (CEAP 2.0) identifies textiles as a priority value chain and calls for measures that extend product lifetimes, increase recycled content and improve collection, sorting and recycling capacities. These high-level commitments are operationalised through domain-specific instruments that collectively shape incentives and obligations for brands, municipalities and waste operators (Hörner et al., 2024).

A cornerstone of the framework is the Waste Framework Directive, which codifies the waste hierarchy and mandates separate collection of textiles by 2025. This provision elevates municipalities as pivotal implementing actors, with direct implications for infrastructure planning, service design and contractual arrangements with producer responsibility organisations and social enterprises. However, the literature notes uneven readiness across EU Member States and municipalities, with persistent gaps in funding, sorting standards, and monitoring systems that affect collection quality and downstream recyclability (Amicarelli and Bux, 2022; Hörner et al., 2024; Maldini and Klepp, 2025). Product-side measures are advancing in parallel. The Ecodesign for Sustainable Products Regulation (EU Regulation, 2024), known as "ESPR", introduces horizontal requirements for durability, reparability, recyclability, and the availability of spare parts. For textiles, the ESPR is expected to interact closely with the EU Strategy for Sustainable and Circular Textiles, which sets the ambition that products placed on the EU market by 2030 be durable, repairable and recyclable, contain recycled fibres and be free of hazardous substances that hinder circularity (Bour et al., 2023).

Complementary consumer-facing provisions aim to reduce premature disposal by ensuring repair services, access to information and non-price remedies that repair a viable option for citizens (Maramura and Ruwanika, 2023). These measures are reinforced by market-surveillance tools and proposed green-claims rules to curb misleading environmental communications. Digital transparency is another regulatory lever. The ESPR foresees the Digital Product Passport as a data architecture to disclose product-level information (e.g., fibre composition, presence of elastane, chemicals of concern, repair instructions, recycled content and end-of-life guidance). For denim, a DPP can support design-for-disassembly, sorting automation and reverse-logistics orchestration, thereby tightening the link between supply-chain traceability and municipal post-collection operations (Cruz and Rosado da Cruz, 2023).

3.5. Discussion

The results of this systematic literature review demonstrate that the transition towards denim circularity is shaped by a constellation of environmental, technical, behavioural and regulatory factors. Rather than emerging as isolated dimensions, these clusters reveal a high degree of interconnection, where environmental imperatives (Cluster 1), supply chain and municipal coordination (Cluster 2), consumer practices and business model innovation (Cluster 3), and regulatory frameworks (Cluster 4) interact in complex and mutually reinforcing ways. Addressing denim waste therefore requires a systemic and integrated approach that recognises these interdependencies and mobilises solutions across multiple levels of governance and practice.

Within this context, this paper identifies the need for a holistic and operational strategy that can

translate EU policy ambitions, such as those articulated in the European Green Deal, the Circular Economy Action Plan, and the EU Strategy for Sustainable and Circular Textiles, into actionable practices at the local scale. The proposed Eco-Circular Denim model responds directly to this gap by conceptualising a smart and participatory municipal framework for denim waste management (Fig. 4). This approach parallels emerging strategies in other complex waste streams, such as battery management, where municipalities similarly balance regulatory compliance with economic constraints in managing hazardous recyclables (Gianvincenzi et al. 2024).

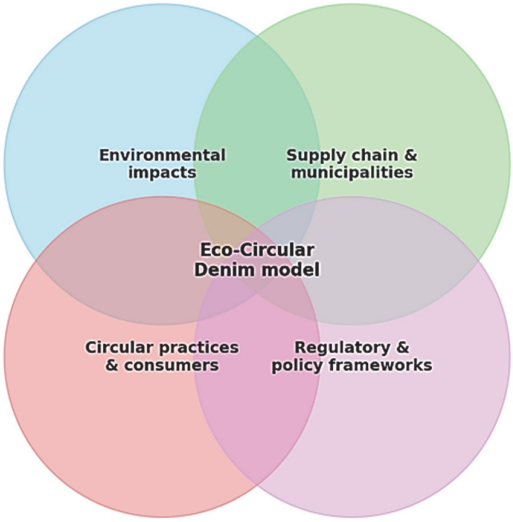

Fig. 4 - Interconnections among the four cluster of Eco-Circular Denim model

As illustrated in Fig. 5, the model embodies the circular economy principle of keeping resources in use for as long as possible by linking upstream and downstream phases of the denim lifecycle. Beginning with raw materials, the framework prioritises organic, recycled, or sustainably sourced cotton and integrates eco-sustainable design principles that enhance durability, reparability and ease of disassembly. These design considerations are complemented by production and distribution processes informed by digital transparency mechanisms such as blockchain and Digital Product Passports, which ensure traceability and accountability across the supply chain. During the consumption phase, the model emphasises practices such as reuse, repair and upcycling, supported by municipal infrastructures and citizen engagement platforms that create incentives for sustainable behaviour. At the post-consumer stage, municipalities emerge as pivotal actors. Empowered by the Waste Framework Directive's mandate for separate textile collection, they coordinate collection, sorting, and redistribution infrastructures, ensuring that denim is directed towards reuse and recycling streams rather than landfilling or incineration. Integration of digital platforms allows real-time monitoring of collection flows, optimisation of logistics and enhanced multi-stakeholder coordination.

Recycling occupies a crucial but carefully framed position in the Eco-Circular Denim model. Consistent with the waste hierarchy, recycling is envisaged not as the primary strategy but as a final step once options for reuse and repair have been exhausted. Fibre-to-fibre recycling, supported by advanced treatment facilities, enables the recovery of high-quality fibres and the substitution of virgin cotton, thereby reducing water consumption, greenhouse gas emissions and reliance on agrochemicals. By framing denim as a recoverable urban resource, the model advances a paradigm shift where textiles no longer constitute "waste" but remain embedded within closed production cycles. Importantly, the Eco-Circular Denim model integrates digital governance tools and multi-stakeholder mechanisms as enablers of this transformation. IoT-enabled smart containers, AI-based analytics and blockchain-based DPPs collectively strengthen traceability, reduce contamination and enhance citizen trust.

Meanwhile, structured governance systems, supported by participatory committees, incentive mechanisms, and clear role allocations across municipalities, brands, recyclers, and citizens, facilitate accountability and ensure alignment with extended producer responsibility requirements. Taken together, this model provides not only an operational strategy for municipalities but also a scalable and replicable framework that directly supports EU objectives. By bridging local infrastructures with European-level policy, it demonstrates how denim, given its ubiquity, technical complexity and environmental burden, can serve as an effective entry point for operationalising circular economy principles within urban contexts. In doing so, the Eco-Circular Denim model strengthens the alignment of environmental, social and economic objectives, supporting the Sustainable Development Goals (SDG 11, SDG 12, SDG 13) while offering concrete pathways for systemic change in textile management.

Fig. 5 - Eco-circular denim lifecycle framework

4. Conclusions

This systematic literature review has demonstrated that achieving circularity in the denim sector demands more than isolated or incremental actions. Instead, it requires a comprehensive and systemic reconfiguration of the textile value chain, involving coordinated interventions across environmental, technical, behavioural and policy dimensions. The 52 studies analysed reveal four interrelated thematic clusters: environmental impacts, supply chains and municipal roles, consumer practices and business model innovation and regulatory and policy frameworks. Together, these clusters highlight both the opportunities and persistent barriers to transitioning towards a circular denim economy.

Denim production imposes a disproportionately high environmental burden compared to other textile categories. This is primarily due to its reliance on cotton cultivation and chemically intensive dyeing and finishing processes, as well as the substantial volume of post-consumer waste it generates. These findings underscore the urgent need for systemic interventions along the denim lifecycle. Fibre-to-fibre recycling holds strong potential to mitigate denim's environmental footprint, particularly in reducing water usage and greenhouse gas emissions. Yet, large-scale implementation remains constrained by technical challenges such as fibre blends, material contamination, and the environmental trade-offs associated with chemical recycling.

Governance and organisational dimensions are equally critical. Municipalities, legally mandated to implement separate textile collection by 2025, are well-positioned to drive circular strategies. However, disparities in financial and infrastructural capacity across regions pose a significant threat to the consistent and effective execution of these responsibilities.

Equally important are consumer practices and the evolution of circular business models. Despite increasing environmental awareness, a notable gap persists between sustainable attitudes and actual behaviours. This disconnect - exacerbated by the fast fashion model - continues to hinder the widespread adoption of reuse and recycling. Innovative business models, such as rental, resale and upcycling, offer promising alternatives, but their success depends on supportive infrastructure, consumer engagement and enabling ecosystems.

On the policy front, the current regulatory landscape provides a solid foundation for transformation, particularly through frameworks that promote durability, recyclability and transparency throughout the textile supply chain. Nonetheless, effective implementation requires better policy alignment, continuous monitoring and adaptation to local governance contexts.

In response to these multifaceted challenges, this study introduces the Eco-Circular Denim model: an integrated, intelligent and participatory municipal framework for the sustainable management of post-consumer denim. As illustrated in Figure 3, the model positions municipalities as pivotal hubs connecting upstream processes - such as sustainable cotton sourcing, eco-design, and responsible production - with downstream systems of collection, reuse, repair, and fibre-to-fibre recycling. Digital technologies—including blockchain, IoT-enabled monitoring, and Digital Product Passports - are embedded to ensure traceability, transparency and efficient resource flows. Consumer engagement mechanisms, such as take-back schemes, repair incentives and awareness campaigns, further support behavioural change. Importantly, the model aligns with the waste hierarchy by positioning recycling as a last resort, following opportunities for reuse and repair.

Given its global scale, material intensity and cultural significance, denim offers a strategic entry point for applying circular economy principles to the textile sector. By aligning municipal-level practices with EU policy ambitions, the Eco-Circular Denim model offers a replicable framework for reducing environmental impact, enhancing supply chain efficiency and supporting the objectives of the European Green Deal and the Sustainable Development Goals.

Despite its contributions, this study has several limitations. First, the review is based on 52 peer-reviewed articles published between 2015 and 2025, which may omit relevant insights from grey literature or other databases. Second, the Eco-Circular Denim model remains at the conceptual stage; its feasibility, scalability and socio-economic impacts have yet to be empirically tested. Third, the evolving nature of EU policy frameworks - particularly the implementation of the Sustainable Products Regulation - demands ongoing monitoring and responsiveness to regulatory change.

To enhance the evidence, base and practical applicability of the model, future research should address the following key areas:

1. Policy harmonisation and governance mechanisms – Investigate how EU directives are operationalised at national and municipal levels, and how municipalities collaborate with producer responsibility organisations to implement separate textile collection.

2. Digital technologies and system optimisation – Evaluate the application of IoT, blockchain, and Digital Product Passports in textile supply chains, with attention to interoperability, data ownership, and consumer trust.

3. Consumer engagement and behavioural change – Explore the effectiveness of interventions such as eco-labelling, behavioural nudges, and community-based initiatives in bridging the attitude–behaviour gap in sustainable fashion.

4. Textile recycling technologies – Conduct empirical assessments of emerging fibre-recovery processes, particularly for blended materials and alternative fibres, to understand their environmental and economic performance.

5. Socio-economic implications at the local level – Examine how circular textile systems can foster job creation, support social enterprises and ensure a fair distribution of costs and benefits, consistent with the principles of a just and inclusive transition.

Addressing these research priorities will help move the Eco-Circular Denim model from theory to implementation, enabling municipalities to design adaptive, digitally supported, and socially inclusive strategies. In doing so, the denim sector can become a frontrunner in operationalising the EU's circular economy vision - providing transferable insights for other material-intensive industries and contributing to a broader sustainable urban transformation.

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