Discover Sustainability

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Exploring the state-of-the-art in traceability within the leather industry with recommendations for future research

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Abstract

The leather industry faces mounting pressure to align with global sustainability and circular economy goals due to its resource-intensive and environmentally burdensome production processes. Traceability has emerged as a critical governance tool for enhancing transparency, accountability, environmental risk management, and sustainable value chain management; however, its conceptualisation and implementation in the leather sector remain fragmented. This paper systematically reviews the academic literature to examine how traceability contributes to transparency, sustainability, and circular economy transitions in the leather industry. Four thematic domains are explored: (i) conceptual and practical foundations of traceability; (ii) technological innovations such as RFID, blockchain, and IoT systems; (iii) the relationship between traceability and transparency; and (iv) traceability as an enabler of sustainability and circularity. The systematic review identifies a persistent gap between technological advancement and governance integration, as traceability initiatives often prioritise technical feasibility over systemic adoption and institutional alignment. The paper reconceptualises traceability as a socio-technical governance capability operating as a multi-layered governance infrastructure that can support environmental risk management and sustainability transformation across leather supply chains. Also, a pragmatic methodological positioning whereby systematic evidence synthesis is complemented by the Appreciative Inquiry strengths-based interpretive lens is applied exclusively to the discussion. Correspondingly, a research agenda that prescribes and describes a sequential pathway for advancing traceability scholarship and practice is proposed. The study concludes that scaling traceability as a transformative governance framework offers a viable pathway for the leather industry to transition from fragmented traceability experimentation toward integrated sustainability governance.

Keywords Leather industry, Bangladesh, Traceability, Sustainability

1 Introduction

The leather industry is a vital sector of the global economy, producing raw materials for a wide range of applications including footwear, apparel, automotive upholstery, and luxury goods [1–3]. The leather industry represents a particularly critical context for sustainability and traceability research due to its structural relationship with resource intensity and waste generation. The leather industry feeds directly into fashion's demand for animal-derived materials, driving intensive resource use and environmental impacts that challenge long-term sustainability. The fashion system is inherently linked to rapid product turnover and disposal cycles, where continuous stylistic change drives linear production and consumption models, contributing significantly to waste accumulation and environmental degradation [4]. These systemic characteristics are reinforced by globalised and multi-tier supply chains that obscure material flows and complicate sustainability governance. Emerging research emphasises that achieving circularity in fashion ecosystems requires the coordination of complex input–output resource exchanges across production stages, often facilitated through digital and data-driven supply chain systems [5]. Within this context, the leather sector is particularly salient, as it combines the environmental intensity of livestock-derived materials with chemically intensive processing stages, thereby amplifying sustainability risks and increasing the need for traceability mechanisms capable of monitoring environmental and social performance across supply networks [6–9].

Given these concerns, sustainability has become a regulatory expectation and strategic imperative for stakeholders across the leather value chain. Governments, industry associations, and increasingly conscious consumers demand accountability and transparency in sourcing and production practices [10]. One of the most frequently proposed solutions to address these challenges is traceability—the systematic capability to track materials and products throughout their lifecycle [11]. Advocates argue that by enabling visibility into sourcing, processing, and distribution activities, traceability systems can enhance regulatory compliance, strengthen consumer trust, and facilitate the transition towards more sustainable practices [12–14].

Despite these promises, the implementation of traceability in the leather industry has been inconsistent. While large multinational brands have begun implementing digital solutions such as blockchain platforms and radio frequency identification (RFID) tagging to improve monitoring and transparency [15], small and medium-sized enterprises (SMEs), which make up a substantial share of the sector, particularly in emerging economies, struggle with limited financial resources, weak infrastructure, and insufficient technical expertise [16–18]. This uneven adoption pattern has resulted in fragmented systems that fall short of comprehensive supply chain integration. Moreover, the academic literature on traceability in leather remains relatively underdeveloped when compared to other industries such as food and pharmaceuticals, where legal mandates have driven widespread adoption [19–23]. This imbalance suggests that while leather faces equally severe sustainability challenges, scholarly and industrial engagement with traceability as a transformative governance tool has lagged.

Recent scholarship has examined digital traceability and sustainability governance across multiple supply chain contexts. Within the leather sector, Chen et al. [2] provide a systematic review of sustainable supply chain management, highlighting environmental performance challenges and governance complexities. More recent studies have explored

blockchain-enabled traceability and certification mechanisms in leather supply chains [15] and examined implementation challenges within tanning industries, particularly in developing country contexts [16]. Notably, Chen et al. [2] provide a comprehensive synthesis of sustainable supply chain management practices, highlighting environmental performance challenges, governance complexity, and stakeholder coordination across leather value chains. Their review offers important insights into sustainability drivers, operational barriers, and policy influences shaping environmental performance within leather production systems. Although they provide a broad sustainability governance overview, their analysis primarily focuses on supply chain management practices and environmental performance outcomes rather than on the structural and technological mechanisms through which traceability systems operate. Traceability is discussed as one of several governance tools supporting sustainability, but the study does not systematically examine traceability as an integrated socio-technical infrastructure linking digital technologies, process-level environmental monitoring, and institutional feasibility constraints. Beyond leather, traceability technologies have also been analysed within luxury product value chains, emphasising brand accountability and sustainability signalling [23]. However, while these studies provide valuable insights into digital traceability technologies and supply chain transparency, they tend to focus either on technological applications or sector-wide sustainability transitions without integrating traceability as a socio-technical governance and environmental process-control mechanism. The leather industry presents a unique analytical context due to its chemically intensive production processes, multi-tiered supply chain fragmentation, and strong interdependence between traceability systems and environmental performance outcomes. Consequently, a sector-specific synthesis that integrates technological, governance, and environmental process-control perspectives remains underdeveloped in current scholarship.

Building on and extending evidence in the extant literature, this paper systematically maps and synthesises peer-reviewed literature on traceability in the leather industry to assess the current state of research, identify knowledge gaps, and propose directions for future research and practice. Against this backdrop, this systematic review critically examines how traceability has been conceptualised, designed, and applied within the leather supply chain, and evaluates its role in advancing sustainability, transparency, and circular economy principles, highlighting both opportunities and persistent barriers. Accordingly, this review asks: (1) How has traceability been conceptualised and operationalised in the leather sector? (2) What governance and technological frameworks underpin its implementation? (3) How does traceability contribute to transparency, sustainability, and circularity? Specifically, it explores four interrelated themes: (i) the concept, context, and importance of traceability, (ii) frameworks, standards, and technological innovations enabling traceability, (iii) the relationship between traceability and transparency, and (iv) traceability as an enabler of sustainability and positive change.

This review provides a focused synthesis of traceability research within the leather sector. While previous leather sector reviews have examined sustainability governance broadly, this study provides a robust systematic synthesis that focuses specifically on traceability as a socio-technical governance and environmental process-control mechanism within leather supply chains. It advances traceability and sustainability governance scholarship through three key contributions. First, the paper provides a theory-level contribution by reconceptualising traceability in the leather industry as a socio-technical

governance system rather than a purely technological or informational tool. By integrating technological infrastructure, institutional feasibility, and environmental process-control considerations, the study extends existing traceability literature toward a more holistic sustainability governance perspective. Second, the study offers a framework-level contribution through the development of an integrated socio-technical traceability framework that maps data flows, stakeholder roles, governance mechanisms, and feasibility constraints across digital traceability architectures. This framework demonstrates how traceability technologies interact across supply chain layers and identifies critical bottlenecks influencing scalability and adoption, particularly among SME-dominated supply networks. Third, the study offers a methodological contribution by integrating a systematic review protocol with a strengths-based interpretive perspective informed by the Appreciative Inquiry 'Discover' phase. This approach goes beyond conventional barrier-focused syntheses, revealing the enabling dimensions of traceability and the scalable sustainability pathways emerging within complex industrial supply chains, and drawing from these to discuss a proposed research agenda (in Sect. 4). The rest of the paper is structured as follows: Sect. 2 outlines the methodological approach; Sect. 3 presents descriptive and thematic analysis of the findings; Sect. 4 identifies areas for future research and discusses study limitations, while Sect. 5 is the conclusion. Supporting data are provided in the Appendix.

2 Methodology

This study adopts a Systematic Review (SR) approach to ensure a transparent, replicable, and comprehensive synthesis of scholarly work on traceability within the leather industry. The SR method enables a structured evaluation of existing evidence while minimising subjective bias [24]. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, this review establishes a clear protocol that defines the research scope, search strategy, inclusion and exclusion criteria, synthesis and discussion procedures. Within the synthesis and discussion, elements of the Appreciative Inquiry '*Discover*' phase were selectively integrated to introduce a strengths-based interpretive lens [25]. This perspective foregrounds existing effective practices and positive capabilities identified in the literature, offering an alternative to a benefits-barriers and deficit-oriented analyses and supporting a more generative understanding of how traceability can inform future sustainability interventions [26]. This interpretive lens was applied only after the evidence base had been established and did not influence the systematic review design, search procedures, or evidence selection. Delimiting its use only to the interpretive stage, as we have done, was essential for maintaining methodological rigour and minimising interpretive bias.

The systematic review protocol—including database search strategy, eligibility criteria, study selection, screening, quality appraisal, and thematic synthesis—was conducted in accordance with established systematic review procedures and PRISMA-aligned reporting standards. Inclusion and exclusion criteria were predefined, applied consistently, and independent of the Appreciative Inquiry framework. Similarly, theme development followed an inductive and evidence-driven synthesis process derived directly from the reviewed literature. The *"Discover"* phase was subsequently applied to the synthesised findings to identify and highlight documented examples of successful traceability initiatives, enabling governance mechanisms, and sustainability innovations within the

leather sector. This approach reflects a pragmatic methodological positioning in which systematic evidence synthesis is complemented by a strengths-based interpretive lens applied exclusively at the discussion stage (Table 1).

2.1 Review framework

The overall review process follows the PRISMA framework to ensure transparency and reproducibility. A PRISMA flow diagram summarises the identification, screening, eligibility, and inclusion stages, providing a clear audit trail of how studies were selected and synthesised [27].

2.2 Search strategy

A systematic and replicable search strategy was developed to identify peer-reviewed literature examining traceability within the leather supply chain. The search process followed PRISMA guidance to ensure transparency, comprehensiveness, and reproducibility.

2.2.1 Database selection

A systematic search was undertaken across a range of multidisciplinary and subject-specific databases to capture the interdisciplinary nature of traceability research, which spans sustainability science, supply chain management, and digital technology studies. Within the EBSCOhost platform, searches were conducted in Environment Complete, GreenFILE, and the Sustainability Reference Centre, given their strong coverage of environmental management, industrial ecology, and sustainability governance literature. To broaden the disciplinary scope, additional searches were carried out in Web of Science and Scopus, both of which provide extensive multidisciplinary coverage and citation indexing of high-quality peer-reviewed literature, and in ABI/INFORM (ProQuest), which offers relevant business and industry-focused and supply chain management publications relevant to traceability adoption and governance practices. The use of multiple databases was intended to minimise publication bias and ensure comprehensive literature coverage.

2.2.2 Search terms

Search terms were developed through an iterative process involving preliminary scoping searches, review of keywords used in foundational traceability and leather sustainability studies, and consultation of domain-specific terminology used within leather production and supply chain literature. The search strategy combined three conceptual domains: (i) *traceability and transparency systems*; (ii) *leather production and supply chains,* and (iii) *upstream raw material processing including tanning, hides and skins.* Synonyms

Table 1 Application of Appreciative Inquiry Discover Phase in Interpreting Findings

AI component	Application in the study
Discover phase	Identification of successful traceability implementations, enabling governance mechanisms, and sustainability-supporting practices documented in leather supply chains

Table 2 Search strings

Search strings
"Traceability Systems" AND "Leather Industry"
"Supply Chain" AND "Leather" AND "Traceability"
"Leather Supply Chain Transparency"
"Traceability Systems" AND "Tanning" OR "Hides and Skins"

Table 3 Thematic areas and number of journal articles

Database + other search	
Thematic area	**Articles included**
Traceability in the leather supply chain (concept, context, and importance)	8
Technological innovations in traceability (or enabling traceability)	20
Traceability and transparency	10
Traceability as an enabler of sustainability, positive change, and circular economy	36

and related terminology were incorporated to search for sensitivity and ensure coverage of variations in terminology across disciplines. Boolean operators (AND/OR) were employed to combine keywords and capture relevant literature across conceptual categories.

2.2.3 Search implementation

The same core search strings were applied across all selected databases to maintain conceptual consistency and comparability of results. Minor syntax adjustments were made where required to accommodate database-specific search interfaces; however, the underlying conceptual search structure remained consistent across platforms. This approach ensured that the review captured literature using a uniform conceptual definition of traceability within the leather supply chain while minimising variation introduced by database-specific search logic. The primary search strings are provided in Table 2.

Advanced search functions were employed in each database to refine results and maximise relevance. To ensure search stability and capture any newly indexed studies, database interrogation was carried out at three separate time intervals, several months apart, with the final search completed in November 2025. Although the total number of hits varied across the search rounds, the number of studies meeting the eligibility criteria remained broadly consistent. The values reported in Table 3 reflect the results from the final search iteration. Full database-specific search strings and search dates are presented in Appendix to ensure transparency and reproducibility.

2.2.4 Snowballing procedure

To further enhance literature coverage, backward and forward snowballing techniques were employed by reviewing reference lists and citation networks of eligible studies. This supplementary step enabled identification of relevant publications that may not have been captured through database searches alone.

2.3 Inclusion and exclusion criteria

Articles were screened in two stages—title/abstract screening followed by full-text review—based on predefined inclusion and exclusion criteria. Only studies meeting all inclusion criteria were retained for synthesis. These criteria are summarised in Table 4.

Table 4 Inclusion and exclusion criteria

Criterion	Description
Inclusion	Peer-reviewed journal articles
	Publications dated 2000 to the present to align with the inception off the Sustainable Development Goals in 2015, allowing 15 years prior to capture any relevant literature in the field
	Studies examining traceability as a central theme within the leather value chain, including raw material sourcing, tanning, manufacturing, or retail processes
Exclusion	Conference papers, theses, book chapters, reports, and white papers
	Articles where traceability is mentioned only tangentially without substantial discussion of its application or impact within the leather sector; as well as review articles, case reports, articles with methodological ambiguity, articles without sufficient data

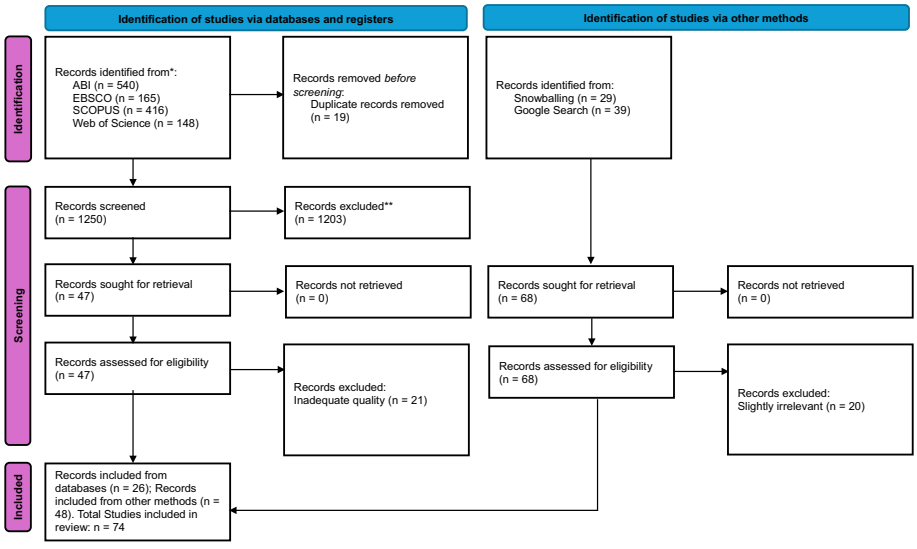

Fig. 1 Result. *Source*: Adapted from Page et al., 2021

2.4 Study selection process

The initial database search yielded a comprehensive pool of 1337 articles. Following duplicate removal and title and abstract screening, 115 studies were retained for full-text review. Of these, 74 studies met the inclusion criteria. These 74 studies form the evidentiary basis for the descriptive and thematic analyses reported in this review (Table 7). Throughout this process, detailed records were maintained in line with PRISMA requirements to ensure traceability of decisions and transparency of the review pathway. A PRISMA flow diagram as shown in Fig. 1, summarising the number of studies identified, screened, excluded, and included, was developed to illustrate the process.

2.5 Data extraction and analysis

Data were extracted from the eligible studies using a structured extraction form that captured key study characteristics—including author(s), year of publication, research purpose, methodological approach and key findings. A thematic synthesis approach [28] was adopted to identify, compare, and aggregate findings across the studies. For this, two reviewers independently coded the data (i.e., selected studies) to capture key concepts and patterns in the original studies that speak to the study's aims and purpose. Subsequently, the codes were grouped into broader themes by these reviewers who later compared notes, and aggregated codes into the four broader and interrelated themes

that summarised the data: (i) the concept, context, and importance of traceability; (ii) frameworks, standards, and technological innovations enabling traceability; (iii) the relationship between traceability and transparency; and (iv) traceability as an enabler of sustainability and positive change (Fig. 2).

The review included conceptual, empirical, and technical studies given the interdisciplinary nature of traceability research. Rather than applying a weighting scheme, studies were synthesised based on their contribution to thematic understanding. Conceptual studies primarily informed theoretical framing and governance interpretation, while empirical and technical studies contributed evidence on implementation practices, technological feasibility, and sustainability outcomes. Quality appraisal guided the relative emphasis placed on each study type during interpretation.

2.6 Quality evaluation

To ensure the robustness and credibility of the synthesis, the methodological quality of included studies was evaluated using a bespoke quality-criteria checklist (Table 8). The checklist was adapted from established qualitative and mixed-method review guidance, including the Critical Appraisal Skills Programme (CASP), as well as general quality standards applied in leading management and organisational research journals (e.g. *Academy of Management Review*; *Journal of Occupational and Organisational Psychology*) [28]. The appraisal criteria focused on three core dimensions: clarity of objectives, methodological transparency and rigour, and relevance to traceability and sustainability research questions within the leather value chain. Each criterion in the checklist was rated on a scale from 0 to 4, where 0 indicated the criterion was absent, 1 low quality, 2 medium quality, 3 high quality, and 4 not applicable.

Quality appraisal was not used as an exclusion criterion, given the emerging and interdisciplinary nature of traceability research, which spans conceptual, empirical, and technical studies. Instead, appraisal results were used to inform the interpretive weighting of evidence during synthesis, with studies assessed as meeting high or moderate quality standards receiving greater emphasis in the analytical discussion. This approach enabled inclusion of diverse evidence types while maintaining analytical rigour and transparency.

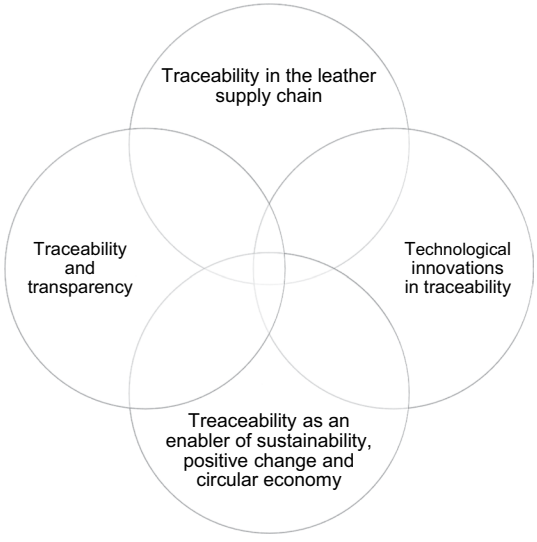

Fig. 2 Mapping the thematic areas

A formal numerical weighting scheme or meta-analytic scoring was not applied, as the objective of the review was conceptual and thematic synthesis rather than statistical aggregation. This approach aligns with established practice in systematic reviews that integrate heterogeneous study designs and theoretical contributions.

To enhance methodological rigour and minimise potential bias, a review panel was established. The panel comprised three researchers with expertise in sustainable supply chains and environmental assessment. The two researchers who conducted the initial selection and thematic analysis were excluded from the panel. They did, however, clarify aspects of what they did with the review panel when called upon to do so. Each member independently reviewed the inclusion and exclusion decisions, selected studies, and synthesis outputs to ensure consistency, transparency, and alignment with the study objectives. The use of a review panel was particularly appropriate for this study given the cross-disciplinary nature of traceability, which intersects technology, sustainability, and value chain governance. This diversity of perspectives enabled a more balanced interpretation of findings and helped validate the thematic structure emerging from the synthesis. Any discrepancies or ambiguities were discussed collectively until consensus was achieved. This iterative peer-review process strengthened the credibility, validity, and reliability of the review, reducing the likelihood of subjective bias influencing interpretation.

3 Descriptive analysis

Following the methodological approach outlined in Sect. 2, the reviewed studies were systematically analysed to extract key insights and patterns relevant to traceability within the leather industry. A thematic synthesis [28] was conducted to identify recurring concepts, enabling factors, methodological design and interrelationships among the studies. A tabular presentation of these is also seen in Table 10 in the Appendix. This dual approach allowed for both breadth and depth of understanding, ensuring that the subsequent findings capture not only prevailing research trends but also the underlying dynamics shaping traceability adoption and sustainability practices in the leather value chain.

3.1 Thematic synthesis

Building on the preceding descriptive analysis, this section presents a thematic synthesis that integrates insights from the reviewed literature on traceability in the leather industry. The synthesis draws on an Appreciative Inquiry (AI) lens, focusing not only on the challenges and gaps identified but also on the strengths, innovations, and enabling conditions that support effective traceability adoption. Four interrelated themes emerged from the analysis: (i) the concept, context, and importance of traceability; (ii) frameworks, standards, and technological innovations enabling traceability; (iii) the relationship between traceability and transparency; and (iv) traceability as an enabler of sustainability and positive change. Collectively, these themes provide a balanced understanding of both the barriers and the success factors shaping traceability implementation, thereby highlighting pathways through which the leather sector can advance transparency, sustainability, and circularity.

3.1.1 Traceability in the leather supply chain

Traceability is widely defined as the ability to record and follow the history, application, or location of a product throughout its life cycle [12]. In the leather sector, this entails monitoring hides from their point of origin, typically cattle farms or slaughterhouses, through tanning, finishing, manufacturing, and ultimately to the end consumer [15, 30]. Effective systems capture information on animal welfare, chemical usage, and labour conditions, thereby constructing a comprehensive record of the supply chain [19, 20]. This holistic visibility is increasingly framed as a prerequisite for sustainable and responsible production [15].

Early academic contributions to the field demonstrate both the promise and limitations of leather traceability. Marconi et al. [12], for instance, proposed a framework linking traceability data with environmental performance indicators in footwear supply chains. Their study illustrated how digital records could strengthen environmental auditing, but it remained narrowly focused on technical feasibility rather than on broader governance implications. Similarly, Cataldo et al. [19] advanced a coding system for hides, which offered operational utility but lacked integration with emerging digital technologies such as RFID and IoT, thereby constraining scalability in global contexts. These examples highlight an important trend in the literature: technical innovations are often explored in isolation, without sufficient attention to systemic adoption and institutional alignment.

The broader supply chain management literature reinforces the significance of traceability as a tool for coordination, risk management, and consumer protection. Alfaro and Rábade [31] emphasised that traceability fosters connection between producers, firms, and retailers, while Dabbene et al. [32] argued that an optimised, sustainable supply chain cannot be achieved without embedding traceability principles. Empirical work from the food sector, where consumer safety concerns and legal mandates are stronger, shows that traceability systems have been crucial for minimising scandals, preventing unsafe products from reaching consumers, and protecting brand reputation [33, 34]. Technological tools such as RFID and 2D barcodes have become dominant in these sectors [35] suggesting potential applicability for leather, depending on the context. However, the transferability of these systems to leather remains underexplored, particularly given the sector's structural complexity and weaker consumer-facing safety regulations.

Beyond sustainability, traceability is increasingly recognised as integral to compliance and quality assurance. Leather products are subject to stringent chemical restrictions, including EU REACH standards limiting azo dyes and chromium VI residues [36, 37]. Gonzalez-Quijano and Luminita [38] note that robust traceability allows brands to trace non-compliance to specific suppliers, mitigating reputational and legal risks. Similarly, Dabbene and Gay [32] underscored traceability's capacity to rigorously document product histories across the chain. Yet Karaosman et al. [39] caution that traceability is still treated predominantly as an operational compliance tool rather than a strategic capability capable of generating competitive advantage and consumer trust. This tension raises critical questions about whether traceability in leather is evolving as a transformative governance mechanism or remains confined to narrow regulatory objectives.

Regardless of increasing attention, traceability adoption across the leather industry is fragmented and uneven. In many developing regions, where a significant share of global leather originates, supply chains are characterized by informality and weak

infrastructure. The leather lifecycle often begins in slaughterhouses [7], but in contexts where such facilities are scarce, hides are collected from small-scale butchers and rural households before being sold to tanneries [40–42]. These conditions create multiple traceability blind spots. Omoloso et al. [21] observed that SMEs in such contexts typically rely on manual record-keeping, leaving data vulnerable to errors or manipulation. The absence of standardised protocols further compounds the problem, producing inconsistencies in data collection and verification across regions [15].

In aggregate, the literature suggests that while traceability is widely acknowledged as essential for sustainability, compliance, and quality assurance in leather supply chains, its current implementation is fragmented, technologically uneven, and poorly integrated with governance frameworks. The focus on technical feasibility, particularly in isolated pilot projects, has overshadowed the more complex questions of institutional alignment, economic viability, and power asymmetries across global supply networks. As a result, traceability in the leather sector remains less a fully realised governance mechanism and more a patchwork of partial initiatives.

3.1.2 Technological innovations in traceability

Technological innovation has become a central enabler of traceability in modern supply chains, progressively replacing traditional methods such as paper-based documentation, batch numbering, and barcoding with advanced digital systems capable of generating real-time, tamper-proof data [20]. Solutions such as radio-frequency identification (RFID), blockchain, and artificial intelligence (AI)-driven analytics are increasingly explored as tools to enhance visibility, integrity, and accountability in global value chains [43–46]. However, their adoption within the leather industry remains uneven, raising questions about cost, scalability, and institutional readiness.

RFID has emerged as one of the most widely tested technologies for traceability in leather and related sectors. Using embedded tags, RFID enables automatic identification and monitoring of hides and finished products across logistics and production stages. Yusoff et al. [47] emphasised its compatibility with green IoT solutions, highlighting efficiency gains in energy use and data transmission. Khan et al. [48] further noted that when combined with IoT sensors, RFID systems can capture environmental conditions such as temperature and humidity during storage and transport, providing assurance of product integrity. Beyond efficiency, RFID has been recognised for its capacity to reduce fraud and substitution risks [19, 49]. Yet, despite these benefits, economic barriers remain significant. Redwood [50] observed that implementation costs are prohibitive for many firms, particularly SMEs, while leather's complex production cycle, especially the tanning stage, remains a persistent weak link where RFID coverage is difficult to implement effectively.

Alongside RFID, blockchain has attracted significant scholarly and industry interest as a potentially transformative technology. Its decentralised and immutable ledger provides an infrastructure for multi-stakeholder trust, reducing risks of data manipulation [45]. Applications in leather include end-to-end visibility of rawhide sourcing, processing, and distribution, thereby addressing concerns over authenticity and greenwashing [13]. Rusinek [51] further highlighted the potential of blockchain-enabled smart contracts to automate compliance verification and streamline payment systems. Integrated with IoT sensors, blockchain can generate a secure digital footprint across the supply chain,

enhancing disclosure on material origins, environmental performance, and end-of-life pathways [9]. However, as Berkesa et al. [18] argue, blockchain's diffusion remains constrained by technical complexity, interoperability challenges, and unresolved questions of scalability, leaving most applications at pilot stage rather than industry-wide adoption.

Empirical studies in adjacent sectors illustrate blockchain's broader potential for circular economy integration. Pautasso et al. [52] demonstrated its application in fashion, enabling companies to disclose raw material origins, production processes, and post-consumer routes. Similarly, Rusinek et al. [51] argued that blockchain can empower consumers to make sustainable purchasing decisions and adopt responsible disposal practices, while also supporting resale markets and recyclers through reliable product authentication and material composition data [53, 54]. Zhang et al. [55] further suggested that combining blockchain with life cycle assessment (LCA) tools could generate accurate data for hotspot analysis and sustainability benchmarking. Supporting this conceptual direction, Shou et al. [45] examined the integration of LCA and blockchain within the fashion sector, highlighting the potential environmental benefits of circular strategies and the role of blockchain in improving traceability and data sharing. However, their work remained largely conceptual, as no practical implementation of blockchain-enabled LCA systems was demonstrated. Consequently, despite these conceptual advances, applied research that empirically links blockchain to LCA in leather remains limited, indicating a significant gap between technological potential and practical deployment that merits further investigation. In recent studies, Islayem et al. [15], employ Ethereum smart contracts blockchain technology to develop a traceability solution that enable end-to-end tracking of leather products across their life cycle, while concurrently establishing a structured framework through which certification bodies can monitor, audit, and validate compliance with sustainability standards. Importantly, the proposed architecture is designed to support scalability, thereby enhancing its economic feasibility for high-volume manufacturing contexts.

Artificial intelligence (AI) and machine learning (ML) offer another frontier in strengthening traceability. By analysing large datasets generated by IoT devices, AI can support anomaly detection, predictive maintenance, and sustainability benchmarking [56, 57]. Wu et al. [46] demonstrated how AI-driven image recognition can verify hide quality at slaughterhouses, while predictive analytics can optimise tanning operations to minimise chemical waste. Similarly, clustering algorithms have been shown to classify animal hides with high accuracy, enhancing sorting and quality assurance processes [58, 59]. Beyond quality control, AI analytics enable proactive risk identification, demand forecasting, and process optimisation, thereby contributing to both efficiency and sustainability objectives across the supply chain [60].

Increasingly, scholars highlight that the most promising advances lie not in isolated applications but in the convergence of blockchain, IoT, and AI. This integrated framework leverages the immutable record-keeping of blockchain, the real-time data collection capacity of IoT, and the predictive insights of AI to overcome the limitations of traditional traceability systems [61]. Singh et al. [62] and Charles et al. [63] emphasised that such synergies can simultaneously address transparency deficits, security vulnerabilities, and weak real-time connectivity that plague conventional methods. Moreover, integrated systems enhance resilience by enabling rapid detection of fraud, disruptions, or product recalls, thereby strengthening risk management [64, 65]. Nevertheless, their

success depends heavily on robust data governance, cross-sectoral interoperability, and collaboration among diverse stakeholders, factors that remain underdeveloped in the leather industry.

The literature indicates that while RFID, blockchain, and AI hold transformative potential, their current deployment in the leather sector is fragmented and experimental. The critical challenge lies not only in technological capability but also in addressing structural barriers such as cost, scalability, and institutional coordination. Without stronger integration into governance frameworks and broader stakeholder alignment, these innovations risk remaining confined to isolated pilots rather than reshaping the leather supply chain at scale.

In addition to RFID, blockchain, and AI applications, Digital Twin (DT) frameworks and smart labelling (e.g. NFC/digital-ID tags) have emerged as potential enablers of advanced traceability. Digital Twins have been successfully deployed in complex manufacturing contexts to create real-time virtual replicas of production systems, integrate IoT data streams, monitor logistics, and support circular-economy workflows [66]. While these features align well with the multi-stage, material-intensive nature of leather processing, their direct use in the leather sector remains sparse. For example, in the textile and apparel industry, Cura et al. [10] demonstrate how traceability and transparency remain critical challenges across the value chain and call for digital solutions to enable chain-of-custody, lifecycle tracking, and circularity.

3.1.3 Towards an integrated socio-technical traceability framework

Although literature frequently examines RFID, blockchain, IoT, and artificial intelligence as discrete technological solutions, traceability in complex global supply chains operates as a socio-technical system in which technological infrastructure interacts with governance arrangements, organisational capabilities, and institutional contexts. Understanding traceability effectiveness, therefore, requires moving beyond technology-centric perspectives toward integrated analytical frameworks that capture data flows, stakeholder control, and systemic constraints.

In an integrated traceability architecture (as shown in Table 5 and illustrated in Fig. 3), IoT-enabled sensors and RFID tagging typically function as primary data capture mechanisms, generating real-time information on product identity, location, and environmental conditions across production and logistics stages [9]. These data streams can subsequently be transmitted to distributed ledger platforms such as blockchain, where transaction records are validated, stored, and secured through decentralised consensus mechanisms [45]. Artificial intelligence and machine learning applications operate at the analytical layer, transforming traceability datasets into actionable insights, including anomaly detection, predictive quality assessment, and sustainability performance monitoring. The processed information is then translated into reporting and verification outputs that inform regulatory compliance, certification schemes, and consumer transparency platforms [62, 63].

Despite the conceptual promise of this layered architecture, several interoperability and governance bottlenecks persist. Technical interoperability challenges arise from incompatible data standards, fragmented digital infrastructures, and inconsistent tagging protocols across supply chain tiers. Equally significant are institutional barriers related to data ownership, confidentiality concerns, and asymmetrical power

Table 5 Socio-Technical integration framework for digital traceability systems

System layer	Primary technologies	Core functions	Key actors	Potential bottlenecks	Feasibility considerations
Data Capture Layer	RFID, IoT Sensors, Digital Tagging	Product identification, environmental monitoring, logistics tracking	Slaughterhouses, tanneries, manufacturers, logistics providers	Inconsistent tagging standards, infrastructure limitations, data entry errors	Technological feasibility generally high; institutional feasibility constrained by cost and training requirements for SMEs
Data Storage & Verification Layer	Blockchain, Distributed Ledger Technologies	Secure transaction recording, tamper-proof data validation, multi-stakeholder data sharing	Brands, certification bodies, technology providers, regulators	Interoperability challenges, data ownership disputes, governance complexity	Technologically feasible but dependent on governance frameworks and stakeholder trust
Data Analytics Layer	Artificial Intelligence, Machine Learning, Predictive Analytics	Sustainability monitoring, anomaly detection, quality control, supply chain optimisation	Manufacturers, brands, auditors, research institutions	Data standardisation gaps, limited dataset quality, technical skill shortages	High technological potential but requires advanced organisational capabilities
Reporting & Transparency Layer	Digital Dashboards, Certification Platforms, Sustainability Reporting Systems	Regulatory compliance reporting, consumer transparency, certification verification	Brands, certification bodies, regulators, consumers	Selective disclosure, lack of standardised reporting metrics	Institutional feasibility dependent on regulatory alignment and stakeholder incentives

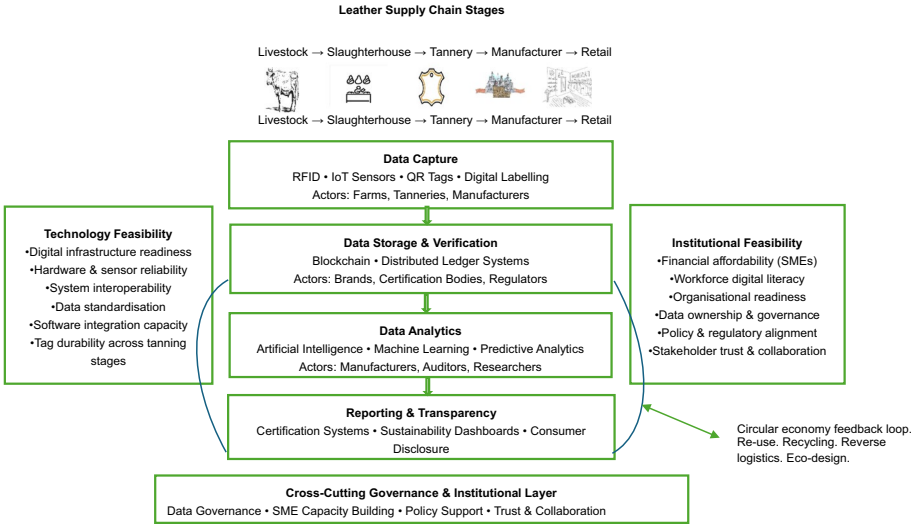

Fig. 3 Conceptual socio-technical framework illustrating data flows, actor roles, and governance mechanisms in integrated digital traceability systems across the leather supply chain. The framework distinguishes technological infrastructure layers from cross-cutting institutional feasibility requirements. The framework distinguishes between technological feasibility, referring to the technical capability and infrastructure required to implement traceability systems, and institutional feasibility, which captures organisational readiness, governance arrangements, financial accessibility, and stakeholder collaboration requirements. Both dimensions operate across all layers of digital traceability systems and jointly determine successful implementation, particularly within SME-dominated supply chains

relationships between supply chain actors. The relevance of business type and the nature of their activities also matter. For instance, suppliers, particularly SMEs and informal operators, may generate traceability data but possess limited control over how such data are accessed, monetised, or utilised by downstream multinational firms. Such dynamics may create trust deficits that can discourage participation in traceability initiatives [23].

Critically, the distinction between technological feasibility and institutional feasibility remains underexplored in existing scholarship. While digital traceability technologies are increasingly capable of capturing and transmitting supply chain data, their adoption depends heavily on organisational readiness, financial resources, workforce digital literacy, and supportive policy environments. Correspondingly, SMEs, unlike their large business counterparts, frequently face disproportionate implementation costs and operational disruptions associated with digital traceability deployment [16]. Without targeted capacity-building programmes, standardised governance frameworks, and equitable data-sharing models, technological innovations risk reinforcing existing power asymmetries rather than promoting inclusive sustainability transitions.

Adopting a socio-technical systems perspective enables a more comprehensive understanding of traceability implementation by recognising that technological infrastructure, governance mechanisms, and organisational capabilities must co-evolve. Such integration is essential for transforming traceability from a technical monitoring tool into a scalable governance framework capable of supporting transparency, sustainability, and circular economy transitions across the leather supply chain. An integrated socio-technical traceability architecture, as illustrated in Fig. 3, demonstrates how digital technologies interact across data capture, verification, analytics, and reporting layers, while highlighting governance and feasibility constraints.

3.1.4 Traceability and transparency

Traceability and transparency, though closely related, serve distinct yet complementary functions within supply chain governance. Traceability refers to the technical capacity to capture, record, and track product information across production and distribution stages [39, 67], whereas transparency concerns the disclosure and accessibility of this information to internal and external stakeholders [68]. In the leather sector, full traceability systems can provide comprehensive data regarding sourcing, manufacturing practices, and associated environmental and social impacts [69]. By leveraging voluntary traceability schemes, standard measurement tools, and technological solutions, companies can substantiate sustainability claims, mitigate ethical and environmental risks, and optimise value chain management [70].

Traceability acts as a prerequisite for transparency. Once accurate data is captured, it can be disseminated to enable informed decision-making by consumers, regulators, and business partners [68, 71]. Transparency provides insight into production processes, helping stakeholders understand and evaluate compliance with environmental, social, and regulatory standards. Critically, while transparency can foster trust and legitimacy, it may also introduce tensions related to power dynamics and competitive advantage within supply chains, as firms may be reluctant to share sensitive information [72, 73].

Reporting practices are a central mechanism for operationalising transparency. Effective reporting requires clarity, consistency, and comparability to support stakeholder confidence [74]. However, studies have shown that sustainability reporting often suffers from selective disclosure, whereby companies highlight positive outcomes while downplaying areas of environmental or social impact that may negatively reflect on them [68]. This selective approach underscores the need for integrated and standardised reporting mechanisms that can enhance the credibility of corporate sustainability initiatives.

Despite the recognised importance of transparency, achieving it in global leather supply chains remains challenging. The multi-tiered and geographically dispersed nature of leather production, coupled with limited regulatory oversight in key sourcing regions, contributes to significant opacity, particularly regarding lower-tier suppliers [21, 75]. While initiatives such as the Global Reporting Initiative (GRI), Leather Working Group (LWG) or Sustainable Leather Foundation (SLF) certifications attempt to standardise disclosure, they often lack independent verification, leaving room for selective reporting and greenwashing [38]. Furthermore, brands must navigate the delicate balance between demonstrating sustainability credentials and protecting commercially sensitive information, which can limit the practical extent of transparency even when traceability systems exist [12].

Technological innovation increasingly provides solutions to the transparency challenge. Digital tools, including blockchain and IoT-based platforms, can facilitate the secure, real-time sharing of supply chain information, enhancing visibility across multiple tiers [76, 77]. Blockchain, in particular, offers immutable ledgers that improve data integrity, support consumer verification of product origin, and enable automated compliance monitoring [78]. However, the successful implementation of these technologies requires strong organizational and supply chain capabilities, including collaborative governance, leadership commitment, and alignment of strategic objectives across network actors [78, 79].

Overall, transparency and traceability should be conceptualised as interdependent pillars of sustainable supply chain management. Traceability provides the technical infrastructure for capturing accurate, actionable data, while transparency ensures this information is accessible, credible, and strategically utilised by stakeholders. Yet, as the literature indicates, current practices in the leather industry remain predominantly voluntary, fragmented, and unevenly enforced. This highlights a critical research gap in understanding how technological, organisational, and regulatory mechanisms can be synergised to achieve meaningful and verifiable transparency across the complex leather supply chain.

3.1.5 Traceability as an enabler of sustainability and circular economy

Traceability, as defined in the ISO 9000 series on quality management, is "the ability to trace history, application, use, and location of an item or its characteristics through recorded identification data" [67, 80]. Traditionally associated with quality and safety management, traceability has increasingly been connected to sustainability and transparency across value chains [81]. The United Nations Global Compact Office [82] expanded this perspective by framing traceability as the ability to trace products, parts, and materials to ensure reliable sustainability claims in human rights, labour, environmental protection, and anti-corruption. Within the leather industry, traceability provides visibility across multiple tiers of the supply chain, supporting regulatory compliance, ethical sourcing, and adherence to social responsibility standards [10]. Moreover, traceability is increasingly regarded as a prerequisite for implementing circular economy (CE) principles, which aim to minimise waste and maximize resource efficiency.

Despite its potential, the adoption of circular practices faces several challenges. Studies in the textile and apparel sector highlight obstacles including limited research and development, lack of appropriate technology, weak regulatory support, high costs, and

low organisational commitment [83, 84]. Additional challenges include inadequate waste management, poor adaptation to existing technologies, and design-related inefficiencies, which restrict the sector's overall sustainability performance [85–87]. These insights underscore that while traceability provides the technical foundation for circular practices, achieving effective sustainability outcomes requires strategic alignment, organisational commitment, and cross-functional collaboration [88, 89].

Integrating circular economy principles into business strategy can amplify their impact [90]. Firms that align CE initiatives with broader organisational objectives can foster collaboration, encourage eco-innovation, and establish circular supply networks [29, 91]. Traceability supports this alignment by providing accurate data on material flows, processing history, and environmental performance, enabling informed decision-making and resource optimisation. Green supply chain management, underpinned by traceable data, further reinforces CE objectives by promoting efficient production and consumption patterns, reducing environmental footprint, and enhancing sustainability performance across the value chain [92].

In the leather industry, traceability enables circular business models such as product take-back schemes, recycling of offcuts, and substitution of harmful tanning agents [13]. By capturing detailed information about material composition and lifecycle processes, traceability facilitates reverse logistics and material recovery, forming the backbone of closed-loop systems. Additionally, it informs eco-design strategies by connecting design decisions to environmental impact, helping companies minimize emissions, water use, and chemical waste throughout the product lifecycle [14, 93]. The successful adoption of circular practices also relies on enablers such as interdepartmental collaboration, stakeholder engagement, and long-term strategic planning, which provide the framework to evaluate cost–benefit dynamics and drive sustainable growth [88, 94]. Viewing these enablers through an Appreciative Inquiry 'Discover' lens highlights the importance of identifying and amplifying what already works well within current traceability practices—such as effective cross-departmental collaboration, stakeholder partnerships, collaborative supplier initiatives, low-impact tanning innovations, or closed-loop recycling models and eco-innovation. This strengths-based perspective complements problem-oriented analyses by focusing on scalable success factors that can accelerate systemic sustainability transitions. Integrating this mindset within future traceability research and practice can therefore strengthen the sector's capacity for systemic learning, cross-sector collaboration, and adaptive governance, ultimately supporting more resilient and sustainable leather value chains.

Although, environmental concerns within the leather sector remain significant since leather manufacturing is resource-intensive, consuming large volumes of water and energy, and generating both solid and liquid waste [46, 95, 96]—the circular economy offers a transformative framework to mitigate these impacts. By shifting from linear production models to closed-loop systems, CE strategies reduce waste, enable material recovery, and optimise resource utilisation [97, 98]. Applied to leather, CE interventions such as recycling solid and liquid wastes, recovering chromium, and reusing leather scraps can significantly diminish environmental harm while generating economic benefits through reduced energy consumption and decreased reliance on non-renewable resources [99, 100]. Consequently, traceability becomes essential for monitoring these

practices, ensuring compliance, and linking sustainability performance to supplier evaluation and investment decisions in cleaner production technologies [14].

Enhancing environmental sustainability in the leather sector requires investment in research and development, adoption of advanced technologies, and robust regulatory frameworks [101, 102]. Key performance indicators such as energy efficiency, greenhouse gas emission reduction, water management, waste management, and life cycle assessment (LCA) are increasingly reported by leather companies to measure sustainability outcomes [103]. Additionally, strengthening government policies, financial incentives, and circular economy regulations is critical to promote the effective implementation of sustainable practices and close existing gaps in the sector [104].

3.1.6 Traceability as a process-control and environmental risk management tool

While traceability is frequently conceptualised as an information transparency mechanism, its application within the leather industry extends beyond supply chain visibility to encompass process control and environmental risk management. Leather manufacturing is characterised by chemically intensive production stages, particularly during beamhouse operations and tanning processes, where hazardous substances including chromium salts, sulphides, acids, and synthetic tanning agents are widely utilised [8, 46]. The environmental and health risks associated with these processes such as chromium discharge, wastewater toxicity, and hazardous solid waste generation are strongly influenced by production practices, chemical dosing precision, and waste treatment efficiency.

Traceability systems can play a critical role in monitoring and controlling these risks by enabling real-time tracking of chemical inputs, process parameters, and waste outputs across production stages [11]. For example, RFID-enabled batch tracking and IoT sensor technologies allow tanneries to record chemical consumption rates, wastewater characteristics, and effluent treatment performance. When integrated with digital traceability platforms, such process-level data can support early detection of environmental compliance deviations, facilitate auditing of chemical substitution initiatives, and enhance monitoring of cleaner production technologies [47, 48].

Furthermore, traceability systems provide essential data infrastructure for evaluating transitions from conventional chromium tanning to alternative tanning methods, including vegetable tanning or chrome-free processes. By linking chemical input data with environmental performance indicators such as water toxicity levels, sludge composition, and emission intensity, traceability can support evidence-based decision-making regarding chemical substitution strategies. This integration is particularly relevant for life cycle assessment (LCA) and sustainability benchmarking, where reliable process-level data remains a major limitation.

Importantly, the effectiveness of traceability as an environmental risk management tool depends on the alignment between technological monitoring capabilities and organisational environmental management systems. Without integration into production control protocols, environmental auditing frameworks, and regulatory reporting mechanisms, traceability risks remaining limited to documentation functions rather than supporting proactive environmental governance. Consequently, framing traceability as both an information system and a process-control infrastructure provides a more comprehensive

understanding of its potential to reduce environmental impacts and improve operational sustainability in leather manufacturing.

4 Research gaps and future research

The literature reviewed highlights that traceability is widely recognised as a critical mechanism for enhancing sustainability, transparency, and circular economy practices in the leather supply chain. Studies emphasise its potential to monitor material flows, ensure regulatory compliance, support ethical sourcing, and facilitate closed-loop business models [12–14]. Technological innovations, including RFID, IoT, blockchain, and AI, offer promising solutions to overcome traditional traceability limitations, enabling real-time data collection, secure record-keeping, and predictive analytics for improved operational and environmental performance [45, 46, 61]. While existing scholarship has significantly advanced understanding of traceability in the leather industry, the evidence base remains fragmented and uneven. Rather than presenting an expansive list of research gaps, future investigations would benefit from a prioritised and sequenced research agenda that reflects both sectoral readiness and methodological feasibility. Based on the synthesis, three interrelated research priorities are proposed. To provide greater clarity and prioritisation, the framework in Table 6, outlining sequencing, methodological pathways, and expected contributions, underpins the proposed research agenda discussed next.

4.1 Establishing empirical baselines and context-specific adoption pathways

The most immediate research need lies in generating robust empirical evidence on how traceability systems are adopted across diverse institutional and production contexts. Current knowledge is disproportionately based on pilot projects or conceptual models, with limited comparative evidence on real-world implementation dynamics.

Future research should prioritise multi-case, cross-country comparative studies examining traceability adoption across developed and developing leather-producing regions. In addition, attention should be given to SME-dominated supply chains, not least because adoption barriers are most pronounced for this business category. At both leather-producing and business category levels, research that identifies efforts representing idiosyncratic seeds of sustainability already embedded within existing systems can inform aspects that support traceability as argued for this in this paper, i.e., enabling infrastructures supporting sustainability transformation rather than just peripheral governance instruments. Specific to methods that lend themselves to achieving the sort of baseline and context-specific understanding referred to here, approaches combining supply chain mapping, stakeholder interviews, and operational performance analysis would enable deeper understanding of adoption drivers, organisational readiness, and cost–benefit dynamics. Longitudinal study designs would further allow researchers to examine how traceability systems evolve over time and influence sustainability outcomes beyond initial implementation phases.

4.2 Designing interoperable digital traceability architectures

Once empirical baselines are established, research that focuses on technological and governance integration challenges that currently limit scalability becomes imperative. Although technologies such as RFID, blockchain and IoT are widely discussed [45, 46,

Table 6 Prioritised research agenda for traceability in the leather supply chain

Priority stage	Research focus	Key research questions	Suggested methodological approaches	Expected contribution
Short-Term: Empirical Adoption and Contextual Pathways	Understanding real-world traceability adoption across supply chain tiers and geographic contexts	• How do SMEs and large firms differ in traceability adoption?	• Comparative multi-case studies	Establishes empirical baseline evidence and identifies context-sensitive implementation models for traceability adoption
		• What institutional, economic, and organisational factors influence adoption?	• Mixed-method research (interviews, supply chain mapping, performance analysis)	
		• How does adoption affect operational and sustainability performance over time?	• Longitudinal adoption studies	
Medium-Term: Interoperable Digital Traceability Architectures	Integration of blockchain, IoT, and AI into scalable and interoperable traceability systems	• How can digital traceability technologies be integrated across fragmented supply networks?	• Design science research	Develops scalable technological and governance frameworks enabling industry-wide traceability implementation
		• What governance structures support multi-stakeholder data sharing?	• Systems engineering and pilot testing	
		• What are the economic and environmental trade-offs of digital traceability infrastructures?	• Techno-economic and environmental modelling	
Long-Term: Traceability-Enabled Circular Economy Transformation	Leveraging traceability data to support closed-loop leather production systems	• How can traceability data support eco-design, reverse logistics, and waste valorisation?	• Participatory action research	Demonstrates how traceability can drive systemic circular economy transitions and measurable sustainability improvements
		• How can traceability systems be integrated with Life Cycle Assessment and material flow analysis?	• Integrated LCA and material flow modelling	
		• What policy mechanisms accelerate circular transitions?	• Scenario and simulation modelling	
Cross-Cutting Priority: Inclusive Governance and Strengths-Based Models	Identifying enabling governance and stakeholder collaboration mechanisms	• What collaborative governance models facilitate traceability adoption?	• Network analysis	Generates inclusive governance frameworks that enhance stakeholder trust, collaboration, and sustainability outcomes
		• How can strengths-based approaches scale successful traceability practices?	• Institutional ethnography	
		• How do power dynamics influence data transparency and participation?	• Appreciative Inquiry-based case studies	

61] as seeds of more sustainable traceability, their interoperability across fragmented supply networks remains poorly understood. Thus, research that explores how better to enhance the ability of different technologies to work together seamlessly, exchange information reliably, and use that in the design of context-relevant traceability architecture is warranted.

Future studies could adopt design science and systems engineering approaches to develop and test interoperable digital traceability architectures. Experimental pilot studies integrating multiple technologies within operational supply chains can provide critical insights into data governance models, system compatibility, and stakeholder trust mechanisms. Additionally, techno-economic assessment models could be developed to evaluate financial viability and environmental trade-offs of digital traceability infrastructures, particularly for resource-constrained producers. Such research would move beyond technological optimism by identifying scalable, context-appropriate implementation pathways. This ties with the Appreciative Inquiry approach that recognises

and reinforces the existence of a culture of innovation which can be supported through stronger coordination and investment.

4.3 Operationalising traceability for circular economy transformation

Longer-term research should investigate how traceability systems can be leveraged to enable fully circular leather value chains. While existing literature frequently highlights the potential integration of traceability and LCA [18, 21], empirical demonstrations of how traceability-generated data directly informs circular design, reverse logistics, and waste valorisation remain limited.

Future studies should, therefore, prioritise the development of integrated analytical frameworks that combine digital traceability data with LCA modelling and material flow analysis. For this, participatory action research involving manufacturers, recyclers, and technology providers could test how traceability supports closed-loop production systems in real-world settings. Furthermore, simulation modelling and scenario analysis could assess how policy instruments, certification schemes, and financial incentives interact with traceability infrastructures to accelerate circular economy transitions.

4.4 Cross-cutting priority: strengths-based and inclusive governance models

Across all research stages, greater attention should be given to governance and institutional enablers of traceability adoption. Existing research tends to emphasise barriers, often overlooking successful collaborative practices emerging across supply chains. Future studies could therefore apply strengths-based frameworks, including Appreciative Inquiry, to systematically identify scalable best practices, public–private partnership models, and stakeholder engagement strategies that foster sustainable traceability ecosystems. Network analysis and institutional ethnography represent promising methodological approaches for capturing these relational dynamics.

Taken together, the proposed research agenda suggests a sequential pathway for advancing traceability scholarship and practice. While *short-term research* should focus on generating empirical adoption evidence and identifying context-specific implementation models, *medium-term research* should address technological integration and data governance challenges for enabling scalable traceability systems, and *long-term research* leverage these systems to support circular economy transformation and systemic sustainability transitions within the leather sector.

5 Conclusion

This review set out to examine the state of research on traceability within the leather industry and to evaluate its potential as a catalyst for transparency, sustainability, and circular economy transitions. Drawing on an extensive synthesis of peer-reviewed literature, the paper identified four interrelated thematic areas: (i) the conceptualisation and implementation of traceability within the leather supply chain, (ii) the technological innovations driving its evolution, (iii) the interplay between traceability and transparency, and (iv) its role as an enabler of sustainability and circular economy practices. Collectively, these themes reveal that while the academic and policy discourse increasingly recognises traceability as essential to responsible and sustainable production, its real-world application in the leather sector remains fragmented, uneven, and technologically inconsistent.

The findings show that traceability initiatives have largely focused on technical feasibility—developing coding systems, RFID applications, and blockchain pilots—without equivalent attention to governance integration, institutional coordination, and socio-economic context. This has produced a patchwork of isolated innovations that fall short of transforming supply chain governance at scale. Furthermore, while technological convergence across blockchain, IoT, and AI promises unprecedented visibility and accountability, significant barriers persist, including high implementation costs, limited interoperability, weak data governance, and the absence of standardised protocols. Transparency, though theoretically dependent on traceability, continues to be constrained by selective disclosure and asymmetric information-sharing practices, underscoring the need for integrated reporting frameworks that combine credibility, comparability, and inclusiveness.

Equally, the literature establishes that traceability serves as a foundational enabler of sustainability and circular economy models in the leather industry. It supports compliance, facilitates ethical sourcing, and provides the data infrastructure necessary for resource optimisation, waste reduction, and eco-innovation. However, realising these benefits requires more than technical adoption. It demands organisational commitment, interdepartmental collaboration, and supportive policy environments that can translate traceability data into actionable sustainability outcomes. Drawing selectively on the Discover phase of Appreciative Inquiry, the study highlights existing successful traceability initiatives, collaborative governance practices, and emerging digital innovations that demonstrate scalable pathways for sustainability transformation within the leather sector. A research agenda underpinned by the appreciative approach is also proposed.

Overall, this review underscores that the future of sustainable leather production lies in reframing traceability not merely as a compliance requirement, but as a socio-technical governance and environmental risk-management capability. Achieving this vision requires concerted efforts to integrate digital technologies with inclusive policy frameworks, build institutional and human capacity, and foster multi-stakeholder collaboration across global value chains. Doing so would enable the leather industry to advance from fragmented experimentation toward a coherent, transparent, and circular model of production—one that aligns economic competitiveness with environmental stewardship and social responsibility. By repositioning traceability as a socio-technical governance capability rather than a purely informational tool, this review provides a foundation for future research, policy, and practice to leverage traceability systems as catalysts for measurable sustainability and circular economy outcomes in the leather industry and comparable high-impact supply chains. While grounded in the leather industry, the insights generated (particularly, the idea of traceability as a socio-technical governance capability) offer broader relevance for other chemically intensive and multi-tier supply chains seeking to align transparency, sustainability, and circular economy objectives.

Appendix

See Tables 7, 8, 9, 10.

Table 7 Database and other search—journals by number of articles

Database search		Other search	
Journal	**Article Qty**	**Journal**	**Article Qty**
Advances in Production Engineering & Management	1	Analytica	1
Applied Soft Computing	1	Annals of Operations Research	3
Benchmarking: An International Journey	1	Biosystems Engineering	1
Computers and Electronics in Agriculture	1	Business Strategy and the Environment	2
eLearning & Software for Education	1	Computers and Electronics in Agriculture	1
Environmental Science & Technology	1	Computers in Industry	1
Fresenius Environmental Bulletin	1	Elsevier	1
International Food and Agribusiness Management Review	1	Expert Systems with Applications	1
International Journal of Advance Manufacturing & Technology	1	Food Chemistry	1
International Journal of Logistics Research and Applications	1	Food Control	1
International Journal of Production Research	1	IEEE	1
Journal of Business Research	1	IEEE Access	2
Journal of Cleaner Production	3	International Journal of Intelligence Systems	1
Journal of Supply Chain Management Systems	1	International Journal of Production Economics	4
Journal of the American Leather Chemists Association	2	International Journal of Production Research	2
Journal of the Knowledge Economy	1	Journal of Cleaner Production	6
Journal of the Society of Leather Technologists and Chemists	2	Journal Society of Leather Technologists and Chemists	1
Leather and Footwear Journal	1	Logistics and Transportation Review	1
Socio-Economic Planning Sciences	1	Production and Operations Management	1
Strategic Change	1	Resources, Conservation and Recycling	1
Sustainability	1	Scientific Reports	1
Sustainability: Science, Practice, & Policy	1	Socio-Economic Planning Sciences	1
Computers and Industrial Engineering	1	Software Quality Professional	1
Waste Management and Research	1	Supply Chain Forum: An International Journal	1
Journal of Techonlogy Transfer	1	Supply Chain Management	1
		Sustainability	3
		Sustainable Development	1
		Sustainable Operations and Computers	1
		Waste Management	1

Table 8 Quality and assessment criteria

Assessment indices	Criteria	0	1	2	3	4
Purpose	Is there a succinct statement of the research aim?					
	Is the research question or problem clearly defined?					
Relevance	Is the research design appropriate to address the research aim?					
	Is data collected in a manner that addresses the research issue?					
Rigour	Is there an in-depth description of the data analysis process?					
	Is the data presented sufficient to support the findings?					
Credibility	Are the findings clearly presented?					
	Is the credibility or trustworthiness of findings discussed?					
	Are findings interpreted in relation to the research problem?					
Contribution	Is there any contribution to existing knowledge or understanding?					
	Are there any identified areas for further research?					
	Are there clear implications for policy and practice?					

Scores were assigned based on adapted quality appraisal guidance derived from the Critical Appraisal Skills Programme (CASP) and systematic review evaluation frameworks (Pawson et al., 2005). The checklist was designed to accommodate conceptual, empirical, and technical studies to reflect the interdisciplinary nature of traceability research

Scoring criteria were defined as follows: 0 = criterion absent. 1 = low quality. 2 = moderate quality. 3 = high quality. 4 = not applicable

Table 9 Database search + results

S/N	Search string	Database hits				Relevance by title and abstract			
		EBSCO	Web of science	ABI	SCOPUS	EBSCO	Web of science	ABI	SCOPUS
1	"traceability" AND "leather industry"	2	14	53	129	0	5	2	7
2	"supply chain" AND "leather" AND "traceability"	6	13	219	266	3	4	3	8
3	"leather supply chain" AND "transparency"	2	1	3	14	2	0	0	2
4	"traceability systems" AND "tanning" OR "hides and skins"	155	120	265	7	3	1	2	3
		165	148	540	416	8	10	7	20

The results presented in the table correspond to the final search iteration. The database search was conducted across three separate search rounds between September and November 2025 to ensure comprehensive study identification

Table 10 Synthesis tables

Thematic area: Traceability in the leather supply chain (concept, context and importance)		
Key sources	**Methods/approach**	**Main findings**
Redwood (2008). The Challenges of the Leather Industry	Analytical commentary based on industry reports and expert insights	Discusses the structural, environmental, and ethical challenges of the global leather industry, stressing the need for integrated traceability systems to address environmental and social accountability
Aung and Chang (2014). Traceability in a Food Supply Chain: Safety and Quality Perspectives	Systematic review and conceptual framework development	Defines the key components of traceability within food supply chains, emphasising its dual role in ensuring food safety and quality assurance. Identifies challenges such as data standardisation, technological integration, and information sharing—concepts transferable to traceability in other sectors, including leather
Dabbene et al. (2014) Traceability Issues in Food Supply Chain Management: A Review	Literature review and comparative analysis	Explores traceability as a multidimensional construct linking logistics, information, and product integrity management. Emphasises the foundational role of traceability in safety, authenticity, and supply chain trust
Jaegler (2016). A Sustainable Supply Chain in the Leather Sector: Dilemmas, Challenges and Learnings	Qualitative Analysis	Examines sustainability dilemmas in the leather supply chain, including social and environmental trade-offs. Suggests that traceability is vital for mitigating reputational risk, verifying compliance, and achieving sustainable transformation
García Torres et al. (2019). Traceability for sustainability—literature review and conceptual framework	Systematic Literature Review and Conceptual Framework	Develops a conceptual framework linking traceability to sustainability dimensions (economic, environmental, social). Emphasises the importance of cross-sectoral collaboration, governance, and technological alignment to achieve effective traceability in supply chains, including leather
Corallo et al. (2020). A systematic literature review to explore traceability and lifecycle relationship	Systematic Literature Review	Establishes the link between product lifecycle management (PLM) and traceability, showing how traceability contributes to better lifecycle monitoring, knowledge management, and sustainability integration. Provides conceptual insights applicable to the leather value chain
Thematic area: technological innovations in traceability (or enabling traceability)		
Key sources	**Methods/approach**	**Main findings**
Gaci and Mathieu (2011). Study of Indirect Benefits of RFID Deployment: The Case of the Chemical Substances Supply in the European Union	Empirical study using a cost–benefit analysis approach	Demonstrates that RFID enhances supply chain visibility and regulatory compliance for hazardous chemical tracking—offering transferable insights for traceability within leather processing and chemical-intensive sectors
Qian et al. (2012). A Traceability System Incorporating 2D Barcode and RFID Technology for Wheat Flour Mills	System design and applied technological testing	Develops an integrated traceability platform combining RFID and 2D barcode technologies for tracking product flow. Demonstrates how hybrid systems improve accuracy, speed, and reliability of data capture—offering implications for multi-stage manufacturing traceability in sectors such as leather
Kang and Lee (2013). Development of Generic RFID Traceability Services	Experimental system design and simulation testing	Proposes a modular RFID-based traceability service architecture adaptable across industries. Demonstrates efficiency in tracking, identification, and data integration, highlighting the scalability of RFID for industrial applications such as textile and leather processing
Cataldo et al. (2016) *Innovative method for traceability of hides throughout the leather manufacturing process*	Experimental study (tanning using sensing technologies)	Addresses the technical feasibility of distinguishing hides after processing. Permanent identification markers persist through tanning; mark patterns remain detectable via tested sensing technology. This innovation can help reduce fraud and substitutions in raw materials. Limitations include cost, scaling, and real-world deployment

Table 10 (continued)

Thematic area: technological innovations in traceability (or enabling traceability)		
Key sources	**Methods/approach**	**Main findings**
Marconi et al. (2017). Traceability as a means to investigate supply chain sustainability: the real case of a leather shoe supply chain	Process mapping and ICT-based traceability modelling. Case study—leather shoe manufacturer in Italy	Shows traceability systems using ICT tools (RFID, barcoding, and process data logging) enhance visibility and control over sustainability performance. Argues traceability data can provide measurable indicators (e.g., energy, water, waste) for sustainability assessment. However, cost and interoperability remain key barriers for SMEs. Demonstrates practical applicability of traceability for sustainability monitoring
Luca and Iovan-Dragomir (2018). Software Application for Footwear Traceability	Technical and applied research. Development of a software-based traceability solution for footwear manufacturing using database integration and barcode labelling	Demonstrates the implementation of a simple, cost-effective traceability software for small footwear producers. The system ensures each production stage—from material cutting to finishing—is traceable. Highlights digitalisation as key to improving process control and product authentication but notes low digital literacy as a barrier to wider adoption
Yang (2019). "Maritime Shipping Digitalization: Blockchain-based Technology Applications, Future Improvements, and Intention to Use."	Empirical survey and quantitative analysis	Demonstrates that blockchain-based digitalisation enhances tracking accuracy, documentation efficiency, and security, influencing firms' willingness to adopt traceability technologies
Hastig and Sodhi (2020). Blockchain for supply chain traceability: Business requirements and critical success factors	Conceptual and empirical review	Identifies blockchain's potential to provide immutable records for product provenance and ethical verification. Defines critical success factors such as interoperability, trust, and data governance for scaling blockchain traceability systems in industries like leather and fashion
Thakur et al. (2020). A framework for traceability of hides for improved supply chain coordination	Conceptual framework development using design science methodology, supported by semi-structured interviews with Norwegian stakeholders across the leather supply chain	Proposes a comprehensive traceability framework based on RFID tagging and data integration to improve coordination between slaughterhouses, tanneries, and manufacturers. Highlights that real-time traceability enhances supply chain transparency, reduces information asymmetry, and improves quality assurance. Identifies institutional and technological barriers (e.g., data standardisation and cost of adoption)
Zhang et al. (2020). Blockchain-Based Life Cycle Assessment: An Implementation Framework and System Architecture	Conceptual framework and prototype system architecture	Proposes integrating blockchain with Life Cycle Assessment (LCA) to enhance data transparency, immutability, and accuracy in sustainability reporting. Demonstrates how blockchain can operationalise traceability within environmental impact assessments
Fakheri et al. (2022). A sustainable competitive supply chain network design for a green product under uncertainty: A case study	Quantitative modelling and simulation-based optimisation	Proposes a green supply chain network model that integrates sustainability criteria under uncertainty. Highlights how data-driven systems and traceability tools optimise production, distribution, and reverse logistics in the leather industry
Shou and Domenech (2022). *Integrating LCA and blockchain technology to promote circular fashion—A case study of leather handbags*	Case study: Life Cycle Assessment (LCA) plus design of a blockchain-based framework; comparison of baseline vs circular scenarios; environmental impact quantification	Circular scenarios (especially reuse/second-hand) lead to large reductions in environmental impacts (34.8–53.8% lower in many impact categories); blockchain framework can improve reliability of data, enable tracking of hotspots, improve transparency and traceability in data sharing for circular practices
Ahmed et al. (2022). A blockchain- and artificial intelligence-enabled smart IoT framework for sustainable city	Conceptual and technical framework development	Proposes a digital architecture for real-time monitoring and verification across supply chains. Although applied broadly to urban systems, the framework illustrates the enabling potential of blockchain-AI convergence for traceability, transparency, and sustainability in industrial networks such as leather production

Table 10 (continued)

Thematic area: technological innovations in traceability (or enabling traceability)		
Key sources	**Methods/approach**	**Main findings**
Charles et al. (2023). A critical analysis of the integration of blockchain and artificial intelligence for supply chain	Literature review and conceptual analysis	Evaluates how blockchain-AI integration enhances traceability, transparency, and decision-making efficiency in complex supply chains. Identifies technical interoperability and governance as persistent challenges but underscores their transformative potential for industries such as leather
El Akrami et al. (2023). Unleashing the Potential of Blockchain and Machine Learning: Insights and Emerging Trends from Bibliometric Analysis	Bibliometric and scientometric analysis of blockchain and machine learning applications	Identifies convergence trends between blockchain and AI in enhancing traceability, predictive analytics, and supply chain transparency. Highlights increasing interdisciplinary collaborations and industrial applications in sustainability contexts
Hassoun et al. (2023). Implementation of Relevant Fourth Industrial Revolution Innovations Across the Supply Chain of Fruits and Vegetables: A Short Update on Traceability 4.0	Literature synthesis and technology review	Introduces the concept of "Traceability 4.0," showing integrated digital technologies enhance transparency, real-time data sharing, and efficiency in supply chains—with relevance to broader manufacturing sectors including textiles and leather
Hmamed et al. (2024). The Adoption of I4.0 Technologies for a Sustainable and Circular Supply Chain: An Industry-Based SEM Analysis from the Textile Sector	Structural Equation Modelling (SEM)	Analyses how Industry 4.0 (IoT, AI, blockchain) enhances transparency and resource efficiency. Shows that digital technologies are key enablers of traceability, circularity, and stakeholder collaboration—insights transferable to the leather sector
Saidu et al. (2025). Convergence of Blockchain, IoT, and AI for Enhanced Traceability Systems: A Comprehensive Review	Literature Review	Reviews how technological convergence supports real-time data sharing, automation, and transparency in global supply chains. Notes limitations in interoperability and scalability and calls for regulatory harmonisation to enhance system adoption
Thematic area: traceability and transparency		
Key sources	**Methods/approach**	**Main findings**
Alfaro and Rábade (2009). Traceability as a Strategic Tool to Improve Inventory Management: A Case Study in the Food Industry	Case study approach within a food manufacturing firm	Demonstrates how implementing a traceability system enhances transparency, operational efficiency, and inventory control. Suggests traceability systems can serve as strategic management tools, offering insights relevant to inventory and material flow management in leather supply chains
Gonzalez-Quijano et al. (2012). *Transparency of the origin of hides* and *skins in European leather industry*	Overview	Emphasises transparency over the origin of hides and skins is increasingly demanded by regulation, consumers, and industry bodies in Europe. Finds while some origin labelling exists, there are challenges of tracing lower tiers, verifying supplier claims, consistency, and regulatory harmonisation. Suggests transparency initiatives are underway but limited by lack of standardised frameworks and verification mechanisms
Musa et al. (2014). Supply Chain Product Visibility: Methods, Systems and Impacts	Literature review and framework synthesis	Categorises existing visibility and traceability systems, exploring their technological foundations (e.g., RFID, WSN, GPS). Finds improved visibility enhances trust, responsiveness, and sustainability across supply networks—key aspects of traceability and transparency for complex global chains like leather
Moosmayer and Davis (2016). Staking Cosmopolitan Claims: How Firms and NGOs Talk About Supply Chain Responsibility	Qualitative discourse analysis	Highlights how firms and NGOs construct narratives around transparency and accountability in global supply chains. Traceability emerges as a communicative and symbolic mechanism to convey ethical legitimacy and global responsibility

Table 10 (continued)

Thematic area: traceability and transparency		
Key sources	**Methods/approach**	**Main findings**
Jiang et al. (2018). *IKEA: Global Sourcing and the Sustainable Leather Initiative*	Case study using interviews (about 20 face-to-face with IKEA managers in Sweden and China), plus analysis of corporate documents and supply chain mapping	Shows how IKEA implemented supply chain mapping to slaughterhouses (and works toward farm level), developed traceability specifications, audit requirements (animal welfare, worker welfare). Challenges include traceability of small farms, scattered upstream suppliers, loss of transparency in long global sourcing. Demonstrates that traceability is not just technical but also managerial, standard-setting, auditing
Papú Carrone (2019). Traceability and Transparency: A Way Forward for SDG 12 in the Textile and Clothing Industry	Conceptual and policy-oriented analysis	Argues traceability and transparency are indispensable tools for achieving sustainable production and ethical supply chains. Highlights digital traceability as a key enabler of consumer trust and compliance with sustainability reporting
Brun et al. (2020). Supply chain collaboration for transparency	Multiple case studies across luxury fashion and leather sectors	Identifies collaboration, data sharing, and stakeholder alignment as key enablers of supply chain transparency. Demonstrates that traceability systems thrive when supported by trust-based partnerships and clear governance structures
Karaosman et al. (2020). Behind the runway: Extending sustainability in luxury fashion supply chains	Qualitative multiple-case study of luxury fashion brands (including leather goods). Data collected through semi-structured interviews, document analysis, and secondary reports	Reveals that luxury brands adopt traceability to reinforce sustainability narratives, ethical sourcing, and reputation management. However, opacity persists due to complex multi-tiered networks and confidentiality concerns. Argues that true transparency requires supplier empowerment and shared accountability. Traceability systems help manage reputational risk but remain unevenly implemented across the value chain
Thakur et al. (2020). A framework for traceability of hides for improved supply chain coordination	Conceptual framework development using design science methodology, supported by semi-structured interviews with Norwegian stakeholders across the leather supply chain	Proposes a comprehensive traceability framework based on RFID tagging and data integration to improve coordination between slaughterhouses, tanneries, and manufacturers. Highlights that real-time traceability enhances supply chain transparency, reduces information asymmetry, and improves quality assurance. Identifies institutional and technological barriers (e.g., data standardisation and cost of adoption)
Rinaldi et al. (2022). Traceability and transparency: Enhancing sustainability and circularity in garment and footwear	Qualitative and analytical study combining documentary analysis of industry initiatives (EU Ecolabel, Textile Exchange, and UNECE traceability frameworks) with case illustrations from the footwear sector	Demonstrates that traceability and transparency mechanisms are increasingly viewed as prerequisites for sustainable production and circularity. Highlights interoperability and data integrity as key challenges. Emphasises that standardisation and consumer-facing transparency can improve accountability across complex supply chains, including leather. Identifies regulatory momentum in the EU driving traceability innovations (e.g., digital product passports)
Thematic area: traceability as an enabler of sustainability, positive change and circular economy		
Key sources	**Methods/approach**	**Main findings**
Saravanabhavan et al. (2004). Natural Leathers from Natural Materials: Progressing toward a New Arena in Leather Processing	Experimental and comparative study	Demonstrates using bio-based tanning agents reduces toxic waste and enhances environmental performance. Positions green chemistry as a foundation for sustainable traceability, linking material origin to eco-friendly outcomes in the leather value chain
Zouboulis et al. (2012). Leather Production Modification Methods Towards Minimization of Tanning Pollution: "Green Tanning."	Empirical study	Proposes process innovations—such as chrome recovery, low-salt systems, and cleaner production protocols—that support environmental sustainability. Emphasises that these practices facilitate traceability through measurable sustainability indicators in the tanning process

Table 10 (continued)

Thematic area: traceability as an enabler of sustainability, positive change and circular economy		
Key sources	**Methods/approach**	**Main findings**
Paul et al. (2013). Bangladeshi Leather Industry: An Overview of Recent Sustainable Developments	Descriptive and exploratory case study drawing on industry data, policy reviews, and stakeholder perspectives	Reviews environmental improvements in Bangladesh's leather sector following the relocation to Savar. Highlights ongoing challenges with wastewater treatment and solid waste management. Notes traceability and certification schemes are still limited but increasingly recognised as essential for compliance with international environmental standards. Recommends stronger governance and industry-academia collaboration to advance sustainability
Singh and Gupta (2013). Sustainability: A challenge for Indian leather industry	Conceptual paper and policy analysis; Case study—India's leather sector	Outlines the environmental and social challenges of the Indian leather industry—including pollution control, social compliance, and global competitiveness. Identifies traceability and environmental management systems as critical to improving sustainability standards, export readiness, and stakeholder confidence. Recommends stronger enforcement of environmental norms and adoption of cleaner technologies
Kanagaraj et al. (2015). Eco-friendly waste management strategies for greener environment towards sustainable development in leather industry: a comprehensive review	Literature review	Reviews pollution control, waste minimisation, and eco-friendly technologies in the leather sector. Emphasises the role of traceability in monitoring waste flows, enabling cleaner production, and ensuring regulatory compliance. Argues for integrated waste management and circular recovery systems supported by traceable data
Ghisellini et al. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems	Systematic Literature Review and Policy frameworks on circular economy transitions	Explores the role of circular systems and sustainable production in achieving balance between environmental protection and economic growth. While not leather-specific, it highlights how traceability supports resource flow monitoring, waste reduction, and product life-cycle transparency
Brugnoli (2017). *Sustainability in the leather value chain: Global overview, regional and sectoral peculiarities*	Review Study	Identifies that leather industry is increasingly under pressure from regulations, NGOs, and consumer demand to improve environmental and social performance. Traceability of raw materials and animal welfare are listed among the emerging requirements. Shows that operational cost and complexity are increasing due to these requirements; highlights regional differences in how quickly or broadly practices are adopted
Daddi et al. Iraldo (2017). Using Life Cycle Assessment (LCA) to measure the environmental benefits of industrial symbiosis in an industrial cluster of SMEs	Empirical study employing Life Cycle Assessment (LCA)	Demonstrates traceability and environmental accounting tools such as LCA facilitate data exchange among firms, improving resource efficiency and supporting circular industrial ecosystems. Suggests data transparency is key to collaborative sustainability
Marconi et al. (2017). Traceability as a means to investigate supply chain sustainability: the real case of a leather shoe supply chain	Process mapping and ICT-based traceability modelling. Case study—leather shoe manufacturer in Italy	Shows that traceability systems using ICT tools (RFID, barcoding, and process data logging) enhance visibility and control over sustainability performance. Argues that traceability data can provide measurable indicators (e.g., energy, water, waste) for sustainability assessment. However, cost and interoperability remain key barriers for SMEs. Demonstrates practical applicability of traceability for sustainability monitoring
Wu et al. (2017). Recent progress in cleaner preservation of hides and skins	Review Study	Highlights innovative preservation methods (e.g., enzymatic treatments, alternative salting techniques) that reduce environmental load and maintain raw material quality. These technologies indirectly support traceability by maintaining product integrity and standardisation throughout the supply chain

Table 10 (continued)

Thematic area: traceability as an enabler of sustainability, positive change and circular economy		
Key sources	**Methods/approach**	**Main findings**
Govindan and Hasanagic (2018). A Systematic Review on Drivers, Barriers, and Practices Towards Circular Economy: A Supply Chain Perspective	Systematic Literature Review	Identifies key enablers and barriers for implementing circular economy (CE) across supply chains. Finds that traceability and data visibility are crucial for resource efficiency, waste minimisation, and closed-loop systems. Highlights need for stronger policy and technology alignment in sectors such as leather
Rusinek et al. (2018). Blockchain for a Traceable, Circular Textile Supply Chain: A Requirements Approach	Conceptual and requirements analysis approach	Identifies technical and functional requirements for deploying blockchain-enabled traceability in textile supply chains. Argues that blockchain supports circular economy transitions by ensuring product provenance, lifecycle accountability, and consumer confidence
De Marchi and Di Maria (2019). Environmental Upgrading and Suppliers' Agency in the Leather Global Value Chain	Qualitative case study based on global value chain (GVC) analysis	Explores how supplier-level initiatives and agency contribute to environmental upgrading in the leather GVC. Shows that traceability mechanisms strengthen supplier credibility, compliance, and knowledge transfer between global buyers and local producers
Mejías et al. (2019). Traceability management systems and capacity building as new approaches for improving sustainability in the fashion multi-tier supply chain	Conceptual and applied analysis of multi-tier supply chain traceability	Argues that combining traceability management systems with organisational capacity-building strengthens sustainability performance in the fashion supply chain. Demonstrates that enhanced data transparency supports responsible sourcing and waste reduction. Suggests parallels with the leather sector, where multi-tier transparency is critical
Karaosman et al. (2020). Behind the runway: Extending sustainability in luxury fashion supply chains	Qualitative multiple-case study of luxury fashion brands (including leather goods). Data collected through semi-structured interviews, document analysis, and secondary reports	Reveals luxury brands adopt traceability to reinforce sustainability narratives, ethical sourcing, and reputation management. However, opacity persists due to complex multi-tiered networks and confidentiality concerns. Argues true transparency requires supplier empowerment and shared accountability. Traceability systems help manage reputational risk but remain unevenly implemented across the value chain
Kazancoglu et al. (2020). A Conceptual Framework for Barriers of Circular Supply Chains for Sustainability in the Textile Industry	Conceptual model development based on literature and expert insights	Identifies organisational, technological, and regulatory barriers to implementing circular supply chains. Suggests traceability as a foundational mechanism for overcoming information asymmetry and improving collaboration, with relevance to the leather value chain
Maranesi and De Giovanni (2020). Modern Circular Economy: Corporate Strategy, Supply Chain, and Industrial Symbiosis	Theoretical and conceptual analysis using corporate strategy and supply chain perspectives	Explores the integration of circular economy principles into corporate and supply chain strategy. Highlights traceability systems are essential for supporting industrial symbiosis, material tracking, and sustainability-driven innovation
Moktadir et al. (2020). Circular economy practices in the leather industry: A practical step towards sustainable development	Multi-Criteria Decision-Making Approach	Identifies key circular economy practices in the leather industry—such as waste reuse, process redesign, and material recovery. Emphasises traceability and transparency underpin successful circular models by enabling life-cycle visibility and compliance monitoring
Chojnacka et al. (2021). Progress in sustainable technologies of leather wastes	Review Study	Highlights advances in waste valorisation and recovery technologies (collagen extraction, enzymatic treatment, biopolymers) as key to achieving circularity. Suggests improved traceability of waste streams supports compliance, accountability, and sustainable innovation
Davis et al. (2021). The Evaluation of the Detection of Cr(VI) in Leather	Laboratory-based analytical testing and chemical assessment	Assesses detection techniques for chromium (VI) contamination in leather products. Highlights traceability in chemical sourcing and monitoring as a critical component for ensuring environmental safety and compliance with sustainability standards

Table 10 (continued)

Thematic area: traceability as an enabler of sustainability, positive change and circular economy		
Key sources	**Methods/approach**	**Main findings**
Dhiman and Mukherjee (2021). Biotechnological approaches towards treatment and recycling of wastewater from tanneries and leather industry	Review Study	Demonstrates how biotechnology enhances cleaner production and waste recycling in the leather industry. Highlights the role of traceability in monitoring effluent quality, ensuring compliance, and verifying sustainable practices
Lahane and Kant (2021). A Hybrid Pythagorean Fuzzy AHP–CoCoSo Framework to Rank the Performance Outcomes of Circular Supply Chain due to Adoption of Its Enablers	Quantitative modelling using a hybrid Pythagorean Fuzzy AHP–CoCoSo framework	Demonstrates that traceability is a critical enabler in circular supply chains, enhancing waste reduction, process control, and stakeholder confidence. Highlights the interconnection between digital monitoring and improved sustainability performance
Brun and Ciccullo (2022). Factors affecting sustainability-oriented innovation in the leather supply chain	Qualitative multiple—case study of European leather manufacturers and policy analysis	Identifies key enablers of sustainability-oriented innovation (SOI), including digitalisation, traceability systems, and collaborative governance. Demonstrates traceability fosters innovation by improving visibility, supplier accountability, and eco-design processes. Stresses the role of inter-firm cooperation, leadership commitment, and regulatory alignment in scaling sustainability performance
Fakheri et al. (2022). A sustainable competitive supply chain network design for a green product under uncertainty: A case study of Iranian leather industry	Quantitative optimisation modelling. Case study—data from Iranian tanneries	Demonstrates how sustainability-oriented design (including waste recycling and eco-material selection) can improve cost efficiency and competitiveness under uncertainty. Suggests the need for digital systems to integrate sustainability and traceability data for effective network design
Rinaldi et al. (2022). Traceability and transparency: Enhancing sustainability and circularity in garment and footwear	Qualitative and analytical study combining documentary analysis of industry initiatives (EU Ecolabel, Textile Exchange, and UNECE traceability frameworks) with case illustrations from the footwear sector	Demonstrates traceability and transparency mechanisms are increasingly viewed as prerequisites for sustainable production and circularity. Highlights interoperability and data integrity as key challenges. Emphasises standardisation and consumer-facing transparency can improve accountability across complex supply chains, including leather. Identifies regulatory momentum in the EU driving traceability innovations (e.g., digital product passports)
Shou et al. (2022). *Integrating LCA and blockchain technology to promote circular fashion – A case study of leather handbags*	Case study: Life Cycle Assessment (LCA) plus design of a blockchain-based framework; comparison of baseline vs circular scenarios; environmental impact quantification	Circular scenarios (especially reuse/second-hand) lead to large reductions in environmental impacts (34.8–53.8% lower in many impact categories); blockchain framework can improve reliability of data, enable tracking of hotspots, improve transparency and traceability in data sharing for circular practices
Bui et al. (2023). Causality of Total Resource Management in Circular Supply Chain Implementation Under Uncertainty: A Context of Textile Industry in Indonesia	Quantitative structural equation modelling and causal inference	Although focused on the textile sector, the study provides transferable insights into circular supply chain design under uncertainty. Highlights how traceability mechanisms support total resource management, enhancing resilience and sustainable performance
de Almeida et al. (2023). Best Environmental Practices in the Leather Sector: A framework for circular economy initiatives based on the views of specialists and researchers	Qualitative study using Delphi method	Develops a framework of environmental best practices focusing on waste minimisation, eco-design, and by-product valorisation. Traceability is identified as a foundational enabler for implementing circular economy strategies and verifying compliance. Emphasises collaborative governance, innovation, and transparency as key drivers of sustainable transformation

Table 10 (continued)

Thematic area: traceability as an enabler of sustainability, positive change and circular economy		
Key sources	**Methods/approach**	**Main findings**
Van Opstal and Borms (2023). Startups and Circular Economy Strategies: Profile Differences, Barriers and Enablers	Empirical study using survey and comparative analysis of circular startups	Identifies traceability technologies (digital ledgers, material passports) as important enablers for scaling circular business models. Finds firms adopting traceability achieve better supply chain coordination, consumer trust, and transparency
D'Adamo et al. (2024). Fashion Wears Sustainable Leather: A Social and Strategic Analysis Toward Sustainable Production and Consumption Goals	Mixed-method study integrating literature synthesis, consumer survey, and strategic analysis using stakeholder and social impact lenses	Finds growing consumer preference for sustainably produced leather goods, influenced by traceability and certification schemes (e.g., LWG, ISO 14001). Shows firms investing in transparent traceability and eco-labelling strategies report improved brand trust and competitive advantage. Highlights a gap between consumer awareness and actual willingness to pay, suggesting the need for communication strategies that link traceability to social and environmental outcomes
Maliha et al. (2024). Circular economy practices in the leather products industry toward waste valorization: An approach of sustainable environmental management	Integrative review and conceptual analysis. Case study examples—Asian leather industries (particularly Bangladesh and India)	Finds circular economy adoption in the leather sector remains fragmented, hindered by limited technological uptake, lack of traceability systems, and weak regulatory enforcement. Suggests digital traceability tools (e.g., blockchain and RFID) could enable closed-loop production, enhance material recovery, and facilitate sustainability certification. Calls for stronger stakeholder collaboration and policy incentives to drive circular innovation
Rashid et al. (2024). A Fuzzy Multi-Criteria Model with Pareto Analysis for Prioritizing Sustainable Supply Chain Barriers in the Textile Industry: Evidence from an Emerging Economy	Quantitative fuzzy MCDM and Pareto analysis	Identifies that traceability, digitalisation, and supplier collaboration are pivotal to overcoming key sustainability barriers. Suggests traceability-driven monitoring enhances sustainable supply chain performance
Ahmadi et al. (2025). Environmental and energy analysis of chromium recovery from residual tanned leather using alkaline thermal hydrolysis	Experimental life cycle and energy analysis of chromium recovery processes	Finds alkaline thermal hydrolysis significantly reduces energy consumption and hazardous waste compared to conventional methods. Demonstrates the potential for resource circularity and traceability in waste valorisation, contributing to a closed-loop leather production model
Berkesa et al. (2025). Green supply chain management: Practices and drivers in the Ethiopian leather and leather product industry	Mixed-methods approach combining surveys and interviews. Case study—Ethiopian leather manufacturers and exporters	Identifies key drivers of green supply chain practices, including regulatory pressures, buyer expectations, and competitive advantage. Finds that traceability enhances accountability, waste management, and eco-certification, positioning it as a crucial tool for achieving sustainable operations in developing country contexts
Hashem et al. (2025). Barriers to Product Return in a Circular Supply Chain: A Case from a Retailing Industry	Case study using Analytical Hierarchy Process (AHP)	Finds that enhanced traceability in reverse logistics can improve waste recovery and product lifecycle extension. Recommends investment in tracking systems and consumer engagement to strengthen circularity outcomes
Nath et al. (2025). Circular Economy in a Developing Country's Textile and Apparel Industry: Managerial Perspectives on Challenges and Motivators	Semi-structured interviews. Case study—Bangladesh's textile and apparel sector	Reveals that traceability systems enhance brand credibility and environmental accountability, motivating firms to adopt circular practices. However, financial and policy barriers limit implementation in developing contexts

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Author contributions
Study conceptualization: OO and CDU. Study design: CDU, AO and OO. Data Collection: AO and FMO. Data Analysis: AO, CDU, EL, and OO. Manuscript Writing: AO, CDU, FMO, AH-F, EL, DT, EV. All authors revised and finalized the manuscript. All authors approved the final manuscript **.**.

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Data availability
The authors confirm that the data supporting the findings of this study are available within the article itself.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
Amin Hosseinian-Far is an Editorial Board Member of Discover Sustainability. He was not involved in the editorial nor manuscript handling, peer review, or decision-making process for this manuscript. The authors declare no other competing interests.

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