Building Lean, Agile, Resilient, and Responsible (LARR) Leather Value Chains through Industry 4.0–5.0 Transitions

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Building Lean, Agile, Resilient, and Responsible (LARR) Leather

Value Chains through Industry 4.0–5.0 Transitions

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Abstract

India is one of the world’s leading producers and exporters of processed leather, supported by a large livestock base and geographically concentrated tanning clusters. However, leather processing, particularly tanning and finishing, faces intensifying pressure from environmental regulation, buyer-led governance, and certification-driven market access requirements, most notably those of the Leather Working Group (LWG). These challenges are amplified by sector-specific constraints, including biological variability of raw hides, high water and chemical intensity, reliance on shared effluent treatment infrastructure, uneven technological maturity, and persistent skill gaps.

This study develops an integrated Lean–Agile– Resilient–Responsible (LARR) framework tailored to the operational and institutional characteristics of leather processing value chains. Adopting a theorydriven conceptual synthesis supported by secondary industry evidence and certification protocols, the paper makes two contributions. First, it proposes a Digital-Integrated Leather Supply Chain Maturity Model (DIL-SCM) that situates digital adoption within progressive stages of process discipline, workforce capability development, traceability, and environmental control aligned with Industry 4.0 principles. Second, it introduces an Integrated Sustainable Leather Supply Chain Framework (ISLSCF) that links sourcing integrity, green chemistry, resource efficiency, labour welfare, leadership capability, and ESG governance.

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By synthesizing academic literature, LWG audit protocols, and documented industry practices, the study demonstrates how digitalization, workforce development, and responsible process design jointly reinforce lean efficiency, operational agility, compliance reliability, and systemic resilience. Responsibility is positioned not merely as a compliance cost, but as a dynamic organizational capability rooted in leadership commitment, skills development, and social stewardship, underpinning market access, stakeholder trust, and long-term competitiveness. The convergence of Industry 4.0 and emerging Industry 5.0 principles is thus shown to provide a viable pathway for transforming India’s leather sector toward sustainable global integration.

Keywords: Leather processing; LARR framework; Leather Working Group; Industry 4.0; Industry 5.0; labour welfare; leadership development; sustainable supply chains; India.

1 Introduction

The global leather industry is undergoing structural transformation driven by tightening environmental regulation, buyer-led governance, and escalating expectations related to traceability, chemical safety, labour conditions, and social compliance. These pressures are most pronounced in leather processing, where tanning and finishing operations account for the majority of water consumption, chemical usage, occupational exposure risks, and environmental impacts across the value chain. Compliance with regulatory frameworks such as the European Union’s Registration, Evaluation, Authorisation and Restriction of Chemi-

cals (REACH) and California Proposition 65, alongside private certification regimes such as the Leather Working Group (LWG), has increasingly become a prerequisite for participation in premium export markets.

India occupies a strategically important position within this evolving landscape as a major exporter of wet blue, crust, and finished leather. Despite this position, the sector continues to face persistent structural constraints, including variability in raw hide quality, dependence on Common Effluent Treatment Plants (CETPs), rising compliance costs, limited automation among micro, small, and medium enterprises (MSMEs), uneven

enforcement across tanning clusters, and chronic shortages of skilled technical and supervisory personnel. Weak leadership pipelines and limited succession planning further exacerbate operational fragility, particularly in family-owned and cluster-based tanneries.

Incremental compliance responses or isolated technology upgrades have proven insufficient to address these systemic challenges. Instead, a value-chain-level transformation integrating technology, operational processes, governance mechanisms, and human capabilities is required. This paper argues that competitiveness, sustainability, and resilience in leather processing cannot be achieved through fragmented interventions but require an integrated capability framework.

Accordingly, this study addresses the following research question:

How can Industry 4.0–5.0-enabled Lean, Agile, Resilient, and Responsible (LARR) capabilities be systematically integrated to enhance sustainability, resilience, and global competitiveness in leather processing value chains?

2. Literature Review and Research Gaps 2.1 Sustainable and Responsible Leather Sup - ply Chains

Sustainable supply chain management literature empha-

sizes the integration of environmental, social, and economic objectives across value chains (Ahi & Searcy, 2013; Govindan et al., 2016). In the leather sector, sustainability challenges are amplified by chemical-intensive processes, wastewater generation, and occupational health risks (Kanagaraj et al., 2012; Kanagaraj et al., 2020a). Buyerled governance and private standards, particularly LWG certification, have emerged as de facto regulatory mechanisms shaping supplier behaviour and market access (Ethical Trade Initiative, 2025).

While compliance frameworks have improved environmental and chemical management performance, scholars caution that certification-driven sustainability risks becoming procedural rather than transformative if not embedded within core operational and human systems (Zhu et al., 2013; Sarkis et al., 2011).

2.2 Lean, Digitalization, Industry 4.0–5.0, and Human-Centric Manufacturing

Lean and Six Sigma methodologies have demonstrated potential to improve yield stability, reduce rework, and enhance resource efficiency in leather processing. However, their effectiveness is contingent on operator skill, supervisory capability, and leadership commitment (Bhamu & Sangwan, 2014; Rahman & Ogunleye, 2021). Empirical evidence suggests that lean systems deteriorate without continuous training, standard work discipline, and leadership-led problem-solving cultures (Liker, 2004).

Industry 4.0 technologies, such as automation, sensors, enterprise resource planning (ERP) systems, and digital traceability platforms, can further amplify these gains by enabling real-time monitoring, predictive quality control, and audit-ready documentation (Schwab, 2016; Gunasekaran et al., 2018). However, digital adoption without corresponding investment in workforce capability and change management often leads to underutilization and operational risk (Moktadir et al., 2018).

The emerging Industry 5.0 paradigm addresses these limito

tations by emphasizing human–technology collaboration, worker wellbeing, skills development, and ethical governance as core design principles (European Commission, 2021; World Economic Forum, 2020). Despite this shift, empirical and conceptual integration of operational excellence, digitalisation, sustainability, and human capability development remains limited in the leather sector.

2.3 Research Gaps

Three gaps motivate this study:

a. Limited system-level frameworks addressing leather value chains rather than isolated firms or technologies;

b. Insufficient integration of lean efficiency, agility, resilience, responsibility, and digitalisation within an Industry 4.0–5.0 continuum;

c. Under exploration of leadership capability, workforce training, labour welfare, and succession planning as foundational enablers of responsible and resilient leather processing systems.

These gaps directly inform the development of the LARR framework and the associated research hypotheses.

3. Conceptual Framework: LARR in Leather Processing

The proposed LARR framework conceptualizes four interdependent capability domains:

Lean: Optimization of water, chemical, energy, and labour inputs through standardized work, skill- based task allocation, and continuous improvement;

Agile: Flexibility in processing routes, batch sizes, and product specifications enabled by cross- trained teams and decentralized decision-making;

Resilient: Capacity to absorb regulatory, supply, demand, and workforce-related disruptions through redundancy, skill depth, and leadership continuity;

Responsible: Alignment with environmental, chemical, and social standards—including LWG requirements on worker health, safety, training, and welfare.

Conceptual Proposition

LARR practices compel organizations to redesign not only processes but also people systems, fostering leadership accountability, workforce competence, and organizational learning. These integrated capabilities enhance operational efficiency, sustainability performance, risk management, and social legitimacy, ultimately reinforcing stakeholder trust and industry competitiveness. The effectiveness of LARR adoption is moderated by buyer and regulatory pressure, digital maturity, leadership capability, and market volatility. Responsibility is positioned not merely as regulatory compliance, but as a strategic organizational capability embedded in leadership development, succession planning, worker welfare, and ESG-oriented governance.

Building on Industry 4.0 principles, this study proposes a Digital-Integrated Leather Supply Chain Maturity Model (DIL-SCM) that conceptualizes digital adoption not as a standalone technological upgrade, but as a progressive capability development process. The model situates digitalisation within sequential stages of process discipline, workforce capability development, traceability integration, and environmental control, reflecting the operational realities of leather processing clusters.

Stage 1: Process Stabilisation.

This stage focuses on establishing standard work, basic lean practices, and manual data capture systems, which together provide the operational discipline and data reliability required as a foundation for any meaningful digital adoption.

Stage 2: Digitally Enabled Process Control.

At this level, enterprise resource planning (ERP) systems, batch-level tracking, and basic automation are introduced

enhance process visibility and consistency; however, effective workforce training becomes critical to ensure these technologies are appropriately utilised rather than underexploited.

Stage 3: Integrated Traceability and Compliance.

Digital capabilities expand to enable end-to-end material traceability from raw hide sourcing through to finished leather, supporting alignment with Leather Working Group (LWG) audit requirements and increasing transparency for global buyers.

Stage 4: Predictive Environmental and Quality Control.

Advanced sensing technologies and real-time monitoring systems are deployed to optimise water and chemical usage and improve quality stability, allowing digital systems to support proactive environmental management and regulatory compliance.

Stage 5: Human-Centric Digital Maturity (Industry 5.0 Alignment).

At the highest maturity level, digital tools are embedded within organisational decision-making, skill development, and leadership processes, where technology complements and augments human expertise rather than replacing it, reinforcing long-term sustainability, resilience, and responsible governance.

3.1 Research Hypotheses Development

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H1: Lean Capability Operational and Environmental Performance

Lean process capabilities, characterized by standardized operations, defect reduction, resource optimization, and continuous improvement, positively influence operational efficiency and environmental performance.

H2: Digitalisation as a Lean Capability Multiplier (Industry 4.0)

The adoption of Industry 4.0 technologies positively moderates the relationship between lean capabilities and performance outcomes by enhancing process visibility, traceability, and real-time control.

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H3: Agility Market Responsiveness and Buyer Satisfaction

Agile processing capabilities, such as flexible batch sizing, modular finishing, and rapid design adaptation, positively affect market responsiveness and buyer satisfaction in export-oriented leather value chains.

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H4: Resilience Operational Continuity under Regulatory and Market Shocks

Resilient supply chain capabilities, including water recycling, energy diversification, integrated operations, and market diversification, positively influence operational continuity during regulatory, environmental, and demand-side disruptions.

H5: Responsibility as a Strategic Capability (LWG & ESG Alignment)

Responsible practices, reflected in alignment with LWG standards, chemical management systems, social compliance, and governance mechanisms, positively influence buyer trust, certification outcomes, and export market access.

H6: Leadership, Skills, and Labour Welfare as Enablers of LARR Integration (Industry 5.0)

Leadership development, workforce training, succession planning, and labour welfare practices positively mediate the effectiveness of LARR capability integration, strengthening the relationship between operational practices and long-term sustainability performance.

4. LARR Integration across the Leather Processing Value Chain

Complementing the DIL-SCM, this study introduces an Integrated Sustainable Leather Supply Chain Framework (ISL-SCF) that extends beyond operational efficiency to encompass environmental integrity, social responsibility, and governance capability. The framework conceptualizes sustainability as an interlinked system connecting sourcing integrity, green chemistry adoption, resource efficiency, labour welfare, leadership capability, and ESG-oriented governance across the leather value chain.

Mapping the dimensions:

Sourcing Integrity: This dimension focuses on ethical procurement practices supported by robust traceability systems and active supplier engagement to ensure responsible and transparent upstream sourcing.

Green Chemistry & Environmental Control: Emphasis is placed on the adoption of safer chemical substitutions and systematic alignment with REACH and Leather Working Group (LWG) requirements to reduce environmental impact and regulatory risk.

Resource Efficiency: This dimension addresses the minimisation of water, energy, and waste across all processing stages through disciplined operational control and continuous improvement initiatives.

Labour Welfare & Occupational Health: Focus is given to structured skills training, effective safety management systems, and initiatives that promote worker wellbeing, thereby strengthening social sustainability and workforce stability.

Leadership Capability & Succession Planning: This dimension highlights the importance of managerial continuity, clear ownership of compliance and sustainability responsibilities, and change-oriented leadership to sustain long-term transformation.

ESG Governance: Emphasis is placed on audit readiness, transparent disclosure practices, and buyer–supplier accountability mechanisms that institutionalise responsible behaviour and reinforce stakeholder trust across the leather supply chain.

The ISL-SCF positions responsibility as a strategic, leadership-driven capability that reinforces lean efficiency, operational resilience, and long-term market legitimacy.

4.1 Raw Hide Sourcing

Lean sourcing practices reduce input variability through standardized grading and scientific flaying, supported by training of procurement and inspection personnel. Agility is enabled through multi-region sourcing managed by skilled sourcing teams. Resilience is strengthened through longterm supplier partnerships and leadership continuity in procurement functions. Responsibility is ensured through traceability systems aligned with LWG requirements and ethical sourcing expectations.

4.2 Tanning and Wet Processing

As the most environmentally and occupationally sensitive stage, tanning requires both technological interventions and strong human capability systems. Lean initiatives such as low-water processing, chrome

recovery, and defect reduction depend on operator training and supervisory discipline. Agility is achieved through modular layouts supported by multi-skilled teams. Resilience is enhanced via closedloop water systems, ZLD-enabled CETPs, and succession planning for critical technical roles. Responsibility is embedded through LWG-aligned chemical management, continuous safety training, PPE compliance, and occupational health monitoring.

4.3 Finishing and Export Readiness

Standardized finishing formulations, supported by automation and digital monitoring, improve first-pass yield when combined with operator skill development and quality

ownership. Agile customization is enabled through crossfunctional finishing teams. Resilience is reinforced through portfolio diversification and managerial depth that ensures continuity during workforce turnover. Responsibility is embedded through product-level traceability, audit-ready documentation, and compliance training for quality and compliance staff.

5. Discussion: Industry 4.0–5.0 Convergence and Human-Centric Resilience

The analysis indicates that lean foundations and digital technologies deliver sustainable value only when embedded within robust human systems. Industry 4.0 amplifies process discipline, while Industry 5.0 reframes competitiveness around human capability, leadership continuity, worker wellbeing, and ethical governance.

In Indian leather clusters, responsibility increasingly functions as a dynamic capability that stabilizes operations, reduces compliance risk, enhances labour relations, and strengthens buyer confidence.

Illustrative secondary evidence from leading Indian leather processors (e.g., Tata International, KKSK, Jahan Leather, Prara Leathers) suggests that LARR-aligned practices support certification outcomes, operational stability, and market access. These examples are presented as indicative industry evidence rather than formal empirical testing, highlighting pathways for future quantitative and mixed-method research.

Recent due diligence frameworks (e.g., ETI) increasingly frame sustainability as a shared governance challenge, where buyer purchasing practices, contract stability, and audit behaviour materially influence supplier compliance outcomes. Without alignment between supplier capability development and buyer responsibility, LARR implementation risks reinforcing cost and risk asymmetries within leather value chains. Responsible systems must move from audit compliance to continuous remediation and prevention.

6. Conclusion and Future Research Directions

This study demonstrates that the future competitiveness of India’s leather processing industry will depend not only on technological upgradation and environmental compliance but also on leadership development, workforce capability building, labour welfare, and succession planning. The proposed LARR framework, enabled by Industry 4.0 technologies and guided by Industry 5.0 principles, offers a robust pathway for embedding efficiency, flexibility, resilience, and responsibility into both processes and people systems.

Future research should empirically test the proposed hypotheses using survey-based or longitudinal data across tanning clusters, explore cross-country comparisons, and examine buyer–supplier governance dynamics in greater depth. By integrating human-centric governance into core operations, Indian tanneries can transform compliance from a constraint into a strategic asset, ensuring sustainable participation in global leather value chains.

References

1. Ahi, P., & Searcy, C. (2013). A comparative literature analysis of definitions for green and sustainable supply chain management. Journal of Cleaner Production, 52, 329–341. https://doi.org/10.1016/ j.jclepro.2013.02.018

2. Bhamu, J., & Sangwan, K. S. (2014). Lean manufacturing: Literature review and research issues. International Journal of Operations & Production Management, 34(7), 876–940. https:/ /doi.org/10.1108/IJOPM-08-2012-0315

3. European Commission. (2021). Industry 5.0: Towards a sustainable, human-centric and resilient European industry.

4. Gunasekaran, A., Yusuf, Y. Y., Adeleye, E. O., & Papadopoulos, T. (2018). Agile manufacturing practices: The role of big data and business analytics with multiple case studies.

International Journal of Production Research, 56(1–2), 385–397. https://doi.org/10.1080/ 00207543.2017.1395488

5. Kanagaraj, J., Senthilvelan, T., Panda, R. C., & Kavitha, S. (2015). Eco-friendly waste management strategies for greener leather processing. Journal of Cleaner Production, 89, 1-17.

https://doi.org/10.1016/j.jclepro.2014.11.013 Liker, J. K. (2004). The Toyota way. McGraw-Hill.

6. Moktadir, M. A., Ali, S. M., Kusi-Sarpong, S., & Shaikh, M. A. A. (2018). Assessing challenges for implementing Industry 4.0. Process Safety and Environmental Protection, 117, 730–741. https://doi.org/10.1016/j.psep.2018.04.020

7. Ethical Trade Initiative (2025). Getting started on Leather Due Diligence: A Good Practise Guide for Brands and Retailers. ethicaltrade.org

8. Porter, M. E., & Kramer, M. R. (2011). Creating shared value. Harvard Business Review, 89(1– 2), 62– 77.

9. Schwab, K. (2016). The fourth industrial revolution. World Economic Forum.

10. Zhu, Q., Sarkis, J., & Lai, K. H. (2013). Institutional-based antecedents and performance outcomes of GSCM practices. Journal of Purchasing and Supply Management, 19(2), 106–117.https://doi.org/10.1016/j.pursup.2012.12.001