STUDY OF SELECT ISSUES OF INDUSTRY 4.0 ADOPTION IN APPAREL SUPPLY CHAIN WITH FOCUS ON SUSTAINABILITY AND RESILIENCE

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The Thesis entitled "Study of Select Issues of Industry 4.0 Adoption in Apparel Supply Chain with focus on Sustainability & Resilience in Industry 4.0 era", being submitted by Ms. Neera Singh Parihar to the Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy (Ph.D.) is a record bona fide research work carried out by her. She has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which has attained the standard required for a Ph.D. degree from the Indian Institute of Technology Delhi. The results presented in this thesis have not been submitted elsewhere for the award of any degree or diploma.

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"Life is a journey, and people around you make it happen."

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ABSTRACT

The apparel supply chain represents one of the most complex and geographically spread-out production networks, highly influenced and vulnerable to slightest disruptions arising from environmental, social, political, or natural contingencies. The "new normal" for apparel supply chain management in the post-COVID era, necessitates the adoption and integration of Industry 4.0 principles alongside commercial models that prioritize sustainability with resilient capabilities. Technological innovations and advancements-including Internet of Things (IoT), RFID, cloud computing (CC), cyber-physical systems, innovative manufacturing, sensors, and computer aided design (CAD) technology are increasingly embedded within supply chain networks through unified communication infrastructures, thereby reshaping operational paradigms in accordance with the fourth industrial revolution. Consequently, apparel supply chains must undergo a substantive transformation toward sustainability and resilience, aligning with global environmental imperatives.

Post-COVID-19, apparel supply chains were profoundly disrupted due to the closure of manufacturing units and retail outlets, challenges faced by the migrant workforce, cancellation of contracts, closure of business, reduced manpower allocation, interruptions in raw material supply - particularly from China- alongside mounting pressures related to environmental protection, ethical sourcing, and sustainable practices. These disruptions rendered traditional operations increasingly unsustainable. Consequently, the adoption of digital technologies for operational resilience and sustainable supply chain management became imperative.

The business entities were compelled to conceptualize strategies differently under the "new normal" emphasizing sustainable business models and resilient capability through

Industry 4.0 technologies to enhance supply chain performance. Nevertheless, challenges for adoption of digital technologies were encountered, including high investment cost, lack of knowledge about the technologies, resistance for change and data privacy and security concerns. It is therefore, essential to assess the current situation, requirements, and barriers in implementing advanced technologies in the apparel supply chain (ASC) to foster sustainable and resilient practices for sustaining global business during disruptive situations like a pandemic. For developing countries, where structural constraints persist, this necessitates a comprehensive understanding of the challenges and deterrents that hinder the effective implementation of Industry 4.0, thereby ensuring the establishment of a robust and sustainable apparel supply chain. India occupies an important position in the global textiles & clothing exports, with apparel exports constituting a larger percentage that supplies to the world's leading brands. India benefits from the advantage of availability of resources for apparel production such as fibre, yarn, fabric, well-established garment industry, and a skilled work force. Textiles and apparel account for approximately 5% of India’s total export and capturing larger percentage will require fast adoption of advance technology in the supply chain meeting global sustainable compliances and resilient towards risks.

A critical review and analysis of prior research on apparel supply chains reveals that sustainability and resilience have predominantly been examined as separate dimensions. Existing literature tends to treat these constructs as distinct areas of inquiry, with limited exploration of their integration within supply chain management (SCM). This gap becomes particularly salient in the era of Industry 4.0 and the post-pandemic landscape, where systemic vulnerabilities necessitate the simultaneous consideration of both sustainability and resilience. Accordingly, the present study identifies the need to investigate this intersection and formulates the following research objectives:

- To critically examine the extent to which sustainability and resilience have jointly addressed in apparel supply chain research.
- To analyze the role of Industry 4.0 technologies in enabling sustainable and resilient SC practices in the post-pandemic era.
- To identify the barriers and challenges that hinder the simultaneous adoption of Industry 4.0 for sustainability and resilience in apparel supply chains
- To assess digital readiness, assess technology acceptability in Indian apparel SC
- To propose a conceptual framework that integrates sustainability and resilience within Industry 4.0-driven SCM for the apparel sector

Against this backdrop, the present study contributes to the development of strategies aimed at enhancing industry practices and strengthening supply chain performance through the adoption of Industry 4.0 technologies. By addressing the dual imperatives of sustainability and resilience, the research seeks to provide actionable insights that can guide stakeholders in navigating post-pandemic challenges and advancing toward more robust and future-ready supply chain systems.

The initial phase of the work identifies challenges and develops a framework for supply chain sustainability and resilience in the post-COVID-19 context. The challenges encountered include collaborative participation, rapid responsiveness, product diversification, traceability, environmental, social, and governance (ESG) compliance, regulatory oversights, technological infrastructure, and availability of skilled labor. The study provides a conceptual model along with a final implementable model designed to assist stakeholders- including apparel industry, government agencies, regulatory bodies and policy-makers – in attaining a comprehensive understanding of the issues and challenges faced across different levels of the apparel supply chain in adapting Industry

4.0. Furthermore, the study seeks to identify the Industry 4.0-related issues that influence the sustainable & resilient performance of an Indian apparel industry post pandemic.

The second phase of the study focuses on emerging economies, with particular emphasis on identifying key barriers to Industry 4.0 adoption in apparel supply chains during the post-pandemic period. Subsequently, exploratory factor analysis (EFA) is utilized to cluster items, and identified barriers are examined in detail. The analysis is conducted using 16 items to construct a reliable scale. Total Interpretive Structural Modelling (TISM) is then applied to capture stakeholder relevance and to model the relationships between barrier drivers and dependent variables, thereby developing a hierarchical framework. The challenges are organized into a seven-level hierarchy, and MICMAC analysis is employed to classify them into four categories. By identifying transitive and essential relationships, the study enables stakeholders to pinpoint critical areas requiring greater attention, thereby facilitating the reduction of barriers and advancing the adoption of Industry 4.0.

The third phase of the research examines the digital readiness assessment for Industry 4.0 with focus on sustainability and resilient capabilities, within the Indian apparel supply chain, with particular emphasis on export-oriented manufacturers that play a pivotal role in global apparel exports. The findings indicate that, apart from large-scale apparel enterprises, the adoption of Industry 4.0 processes remains limited as most firms are still at the early “achieving” stage (Level 3). This readiness level is particularly low among small apparel manufacturers. The subsequent phase employs Data Envelopment Analysis (DEA) to evaluate the state-wise performance of the Indian apparel industry, focusing on the input–output mix to determine technical efficiency. The analysis encompasses Overall Technical Efficiency (OTE), Pure Technical Efficiency (PTE), and Scale Efficiency (SE)

across a five-year period (2018–19 to 2022–23). The results reveal that states such as West Bengal, Delhi, Haryana, and Gujarat exhibit the highest efficiency levels and demonstrate notable progress in adopting Industry 4.0 technologies within their operational domains. However, the study also highlights a significant decline in OTE, PTE, and SE during the 2020–21 periods, attributable to the disruptions caused by the COVID-19 pandemic. Further, low average results of IRS & DRS provide insight that the input efficiency requires attention for achieving better performance.

The final phase of the research involves a case study conducted at the factory level, applying the Situation-Actor-Process with Learning-Actions- Performance (SAP-LAP) framework to facilitate the adoption of Industry 4.0 technologies. These include adopting technology like cloud-based audit platforms, sensors, RFID, CAD and cyber-physical systems (CPS), all of which support sustainable practices and ESG implementation. The SAP–LAP model provides benchmarking insights for apparel manufacturers, managers, government policy-makers, suppliers, and industry associations, enabling building organizational capacities with Industry 4.0.

This study concludes by deriving leanings from different phases and synthesis of findings, highlighting major contributions and significant insights made through this research. It discusses the implications for the Indian apparel Industry and provides guidance for policy-makers, regulatory authorities and decision-makers. Finally, the limitations of the research are acknowledged, and the directions of future research are outlined.

Keywords: Apparel, Supply Chain, Industry 4.0, Sustainability, Resilience, SSM, EFA, TISM, Digital Readiness Assessment, Data Envelopment Analysis (DEA), SAP-LAP

सारांश

वस्त्र आपूर्ति श्रृंखला (Apparel Supply Chain) सबसे जटिल और भौगोलिक रूप से फैला हुआ वैश्विक नेटवर्क है, जो पर्यावरणीय, सामाजिक, राजनीतिक कारणों या प्राकृतिक आपदाओं जैसी मामूली गड़बड़ियों से भी अत्यधिक प्रभावित होता है। COVID-19 महामारी के बाद, वस्त्र आपूर्ति श्रृंखला प्रबंधन (SCM) में एक "नया सामान्य" (New Normal) सामने आया है, जिसमें इंडस्ट्री 4.0 (Industry 4.0) सिद्धांतों को स्थिरता-आधारित व्यावसायिक मॉडलों के साथ एकीकृत किया गया है। चौथी औद्योगिक क्रांति के अंतर्गत इंटरनेट ऑफ थिंग्स (IoT), क्लाउड कंप्यूटिंग (CC), साइबर-फिजिकल सिस्टम (CPS), स्मार्ट मैन्युफैक्चरिंग, सेंसर और ब्लॉकचेन जैसी तकनीकों को आपूर्ति श्रृंखला में शामिल किया गया है, जिससे एकीकृत संचार नेटवर्क विकसित हुआ है। यह नवाचार वस्त्र आपूर्ति नेटवर्क को स्थिरता और लचीलापन अपनाने की दिशा में एक बड़ा बदलाव करने के लिए प्रेरित करता है ताकि उद्योग की दीर्घकालिक प्रतिस्पर्धात्मकता और टिकाऊपन सुनिश्चित हो सके।

भारत वैश्विक वस्त्र एवं परिधान निर्यात में एक महत्वपूर्ण स्थान रखता है, जहाँ फाइबर, यार्न, फैब्रिक, तैयार वस्त्र उद्योग और कुशल श्रमिक जैसी आवश्यक संसाधन आसानी से उपलब्ध हैं। वस्त्र और परिधान क्षेत्र भारत के कुल निर्यात का लगभग 5% योगदान देता है। लेकिन COVID-19 के बाद, इस क्षेत्र को कई समस्याओं का सामना करना पड़ा—जैसे कि उत्पादन इकाइयों और खुदरा दुकानों का बंद होना, प्रवासी श्रमिकों की अनुपलब्धता, कच्चे माल की आपूर्ति में बाधा (विशेषकर चीन से), और व्यावसायिक इकाइयों पर नैतिक और टिकाऊ उत्पादन की माँग में वृद्धि। इन चुनौतियों के चलते पारंपरिक संचालन बनाए रखना कठिन हो गया और डिजिटल तकनीकों को अपनाना अत्यावश्यक हो गया। हालांकि, उच्च निवेश लागत, तकनीकी जानकारी की कमी, बदलाव के प्रति विरोध और डेटा गोपनीयता जैसी चिंताओं ने डिजिटलीकरण में बाधा डाली।

इस अध्ययन का उद्देश्य वर्तमान परिदृश्य का मूल्यांकन करना, चुनौतियों की पहचान करना और एक टिकाऊ एवं लचीली वस्त्र आपूर्ति श्रृंखला के लिए उन्नत तकनीकों को लागू करने की संभावनाओं को खोजना है। अनुसंधान के मुख्य उद्देश्य हैं—COVID-19 के प्रभाव का विश्लेषण करना, इंडस्ट्री 4.0 को अपनाने के लिए एक व्यवस्थित ढाँचा विकसित करना, चुनौतियों का अनुकरण करना, भारतीय परिधान आपूर्ति श्रृंखला में डिजिटल तत्परता का मूल्यांकन करना और सर्वोत्तम प्रथाओं का बेंचमार्क करना। शुरुआती चरण में अध्ययन एक ढाँचा प्रस्तुत करता है, जिसमें टीमवर्क, त्वरित प्रतिक्रिया, ESG, नियामक चुनौतियाँ और तकनीकी अवसंरचना जैसे कारकों की पहचान की गई। इसके बाद साहित्य समीक्षा और विशेषज्ञों की प्रतिक्रिया के आधार पर 16 बाधाओं को खोजा गया, जिन्हें EFA के माध्यम से समूहित किया गया। TISM और MICMAC विश्लेषण द्वारा एक सात-स्तरीय चुनौती पदानुक्रम तैयार किया गया।

डिजिटल तत्परता विश्लेषण से पता चला कि बड़े निर्यातक उद्योग इंडस्ट्री 4.0 को तेजी से अपना रहे हैं, जबकि छोटे निर्माता अभी भी प्रारंभिक चरण में हैं। DEA तकनीक का उपयोग करके 2018–2023 के दौरान राज्यवार दक्षता का मूल्यांकन किया गया, जिसमें पश्चिम बंगाल, दिल्ली, हरियाणा और गुजरात उच्च दक्षता वाले राज्य पाए गए। SAP-LAP मॉडल पर आधारित केस स्टडी ने ESG लक्ष्यों के लिए Industry 4.0 तकनीकों (जैसे RFID, क्लाउड ऑडिट सिस्टम, CPS) के व्यावहारिक उपयोग को दर्शाया। यह अध्ययन प्रमुख निष्कर्षों, नीति-निर्माताओं और उद्योग हितधारकों के लिए नीतिगत सिफारिशों और भविष्य के शोध की संभावनाओं के साथ समाप्त होता है।

KEY WORDS & ABBREVIATIONS USED

ASC	-	Apparel Supply Chain
ASI	-	Annual Survey of Industries
AEPC	-	Apparel Export Promotion Council
CC	-	Cloud Computing
CETP	-	Common Effluent Treatment Plant
CFA	-	Confirmatory Factor Analysis
COVID-19	-	Coronavirus disease 2019
CPS	-	Cyber Physical System
CSR	-	Corporate Social Responsibility
DoT	-	Department of Telecommunication
DEA	-	Data Envelopment Analysis
DMU	-	Decision-Making Unit
DRA	-	Digital Readiness Assessment
EFA	-	Exploratory Factor Analysis
ERP	-	Enterprise Resource Planning
ESG	-	Environmental, Social and Governance
EU	-	European Union
GRI	-	Global Reporting Standards
ICT	-	Information, Communication and Technology
IT	-	Information Technology
IoT	-	Internet of Things
IIOT	-	Industry Internet of Things
I 4.0	-	Industry 4.0

ISM	-	Interpretive Structure Modeling
KMO	-	Kaiser-Meyer-Olkin
MICMAC	-	Cross-Impact Matrix Multiplication Applied to Classification
MoSPI	-	Ministry of Statistics and Programme Implementation
MoT	-	Ministry of Textiles, Govt. of India
NSDC	-	National Skill Development Corporation
PCA	-	Principal Component Analysis
RS	-	Resilient and Sustainable
SAP-LAP	-	Situation Actor Process – Learning Action Performance
SC	-	Supply Chain
SCM	-	Supply Chain Management
SDG	-	Sustainable Development Goals
SPSS	-	Statistical Package of Social Sciences
SSM	-	Soft System Methodology
TISM	-	Total Interpretive Structural Modeling
UK	-	United Kingdom
USA	-	United States of America
USD	-	US Dollar
VP	-	Vice President
VoIP	-	Voice conversations across the Internet Protocol
WTO	-	World Trade Organization

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