Title Page

Evaluating Circular Economy and Smart Technology Adoption Barriers in the Indian Textile and Apparel Industries using Neutrosophic ISM

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Abstract:

The rise of globalization and digitization provoked textile and apparel industries worldwide to change their traditional business models. The textile and apparel manufacturing industries are ushering towards adopting novel concepts, viz. smart technologies (ST) due to the advent of industry 4.0 and circular economy (CE) to make their supply chains resilient, sophisticated, and sustainable. This study attempts to identify and evaluate the CE-ST barriers in the Indian Textile and Apparel industries. Eleven significant barriers to CE-ST adoption are identified through an extensive literature review and further validated through a validatory survey using industry experts. This paper utilized a novel form of interpretive structural modeling (ISM) by integrating it with the neutrosophic approach, i.e. Neutrosophic ISM, to compute the driving and dependence power of identified CE-ST barriers. The findings indicate that 'unawareness of adoption policies' and 'lack of government support and subsidies' are critical obstacles to adopting the CE-ST framework in the Indian textile and apparel industries. This research work is the first-of-its-kind to identify and analyze the critical CE-ST barriers in textile and apparel industries and propose strategies to mitigate them. This study offers key strategies to overcome CE-ST barriers to aid practitioners, stakeholders, policymakers, and industry leaders in effectively implementing CE-ST practices in TAI.

Keywords: Barriers, Circular Economy, Smart Technologies, Textile and Apparel Industry, Neutrosophic ISM

1 Introduction

The global textile and apparel industry is growing at a rapid pace, with an estimated market of around US$ 1.9 trillion, reflecting 2% of its involvement in the global GDP of US$ 84.9 trillion (FICCI 2020). European Union and the USA are the dominant players in the global apparel market. India is amongst the top five contributors to the global textile and apparel market and the third-largest exporter in the world, gaining worth US$ 37 billion through textile and apparel exports (FICCI 2020; NITI Aayog 2020). The apparel industry is a significant contributor to the Indian economy. According to the survey by Apparel Export Promotion Council - India (AEPC), the textile and apparel industry (TAI) produces around 7% of industry output and contributes about 4% to the national GDP (FICCI 2020). Around 15% of the total revenues are earned through the exports of textiles and apparel products in India (Dohale, Ambilkar, Gunasekaran, and Verma 2022). Despite these facts and the economic importance of the textile and apparel industry worldwide, it is the second most polluting industry after the oil and gas industry (Muthu 2017). The use of toxic chemicals, water, and land in textile production is majorly responsible for the negative environmental impacts (Muthu 2017, 2019). The critical issue within TAI in India is the waste generated from it. According to estimates, about 25% of fabric wastage occurs during garment cutting and production. This waste is incinerated or thrown directly into the landfill, although there is a high possibility of recycling or reusing many textiles by-products (Khairul Akter et al. 2022; Muthu 2017; Shukla 2020). Ellen MacArthur Foundation (2016) reported that the major sectors, namely construction, textile, food and agriculture, and automobile manufacturing, should focus on implementing a circular economy (CE) to overcome waste management challenges. It is predicted that the CE implementation in these industries can bring an annual benefit of approximately US$ 624 billion, which is equivalent to 30% of the Indian GDP, and reduce around 44% of greenhouse gas emissions by 2050 in India (Muthu 2019). Due to these facts, the TAI practitioners started adopting circular economy practices to remain sustainable and market-competent globally (Brauner et al. 2022; Reike et al. 2022).

On the other hand, the textile and apparel industries are on the cusp of implementing smart technologies. The apparel market is the most dynamic due to continuously evolving fashion trends and ever-changing consumer behavior. Thus, the textile and apparel industries have started ushering toward digital transformations by utilizing smart technologies to address the varying needs for developing technology-oriented sustainable supply chains (Majumdar, Garg, et al. 2021). Plenty of real-life applications are reported in the literature to demonstrate the implementation of smart technologies and industry 4.0 in the textile and apparel industries (Küsters et al. 2017). For example -

- Using smart beams with RFID tags can aid in collecting information related to work-in-progress material (Simonis et al. 2016).
- An OmniPlus air-jet weaving technology developed by Picanol, a Belgian loom manufacturing company, helps to achieve business excellence through smart performance, sustainability, data-driven functioning, and intuitive control (Majumdar, Garg, et al. 2021).
- Uster technologies Ltd. developed a fabric defect identification system for textile industries by deploying image processing and artificial neural network (Majumdar, Garg, et al. 2021).

- The supply chain structure of the textile and apparel industries is intricate and fragmented due to the involvement of different stakeholders that deal with raw materials from multiple sources. Thus, TAI started adopting blockchain technology to maintain traceability within supply chains (Bullón Pérez et al. 2020).
- The deceptive behaviors of consumers resulted in fraudulent returns in the textile and clothing industry (H.-H. Chang and Guo 2021) and witnessed around 50% of frauds in returns (Ülkü and Gürler 2018). Hence, to manage such product returns, blockchain technology (Ar et al. 2020) and "virtual try-on" technology (Yang and Xiong 2019) is implemented (Ambilkar et al. 2021).
- Cognizant has started to develop a blockchain based solution for Apparel & Footwear supply chain traceability for product returns management (Patel et al. 2018)
- Levi Strauss & Co., the American apparel and clothing industry, utilized a blockchain system to enhance the health and safety of outside auditors and workers (Dutta et al. 2020).

Thus, there are enormous possibilities to deploy smart technologies in the textile and apparel industries. Most of the textile and apparel industries in India fall under the umbrella of small and medium enterprises (SMEs). However, previous studies reported that SMEs are not mature enough and well-prepared to implement Industry 4.0 smart technologies due to scarcity of finance, lack of sufficient information technology (IT) infrastructure, and unavailability of a skilled workforce (Majumdar, Garg, et al. 2021). At the same time, textile industries are witnessing difficulties utilizing CE due to a lack of knowledge about CE strategies (Muthu 2019). Unless the barriers to CE-ST are analyzed and the relevant strategies to overcome them are identified, the Indian textile and apparel industries cannot enjoy the benefits and advantages of CE-ST. Therefore, it is essential to investigate the critical barriers of CE-ST adoption in the textile and apparel industry in India.

The existing body of knowledge has highlighted the CE-ST barriers within different Indian industries, such as - CE and industry 4.0 barriers in the automobile sector (G. Yadav et al. 2020), CE barriers in an agricultural supply chain (Yazdani et al. 2019), barriers for IoT adoption in agricultural supply chains (S. Yadav et al. 2020), industry 4.0 adoption barriers in clothing industries (Majumdar, Garg, et al. 2021). However, there is a crucial need of the hour to identify the barriers of adopting CE-ST in the textile and apparel sector and develop strategies to mitigate the barriers. This study attempts to achieve the aforementioned objectives by answering the following research questions (RQs):

RQ 1. What are the critical barriers that hurdle the adoption of circular economy and smart technology (CE-ST) in Indian TAI?

RQ 2. What is the contextual relationship amongst the identified CE-ST barriers?

RQ 3. What are the key strategies and tactics to overcome the CE-ST barriers in TAI?

This current research endeavor aims to make novel contributions to both academia and industry practitioners by addressing the RQs and shed light on several critical aspects concerning the adoption of CE-ST within the Indian textile and apparel industry (TAI). Firstly, it aims to identify the pivotal barriers that impede the seamless integration of CE-ST practices into the TAI sector. Secondly, the study seeks to unravel the intricate contextual relationships existing among the identified CE-ST barriers. Lastly, the research intends to uncover the essential strategies and tactics that can be employed to effectively overcome the CE-ST barriers in the TAI domain. Through these research questions, a comprehensive exploration of the challenges and potential solutions in the adoption of CE-ST within the Indian TAI sector is pursued.

This research utilized a novel type of interpretive structural modeling (ISM) approach, which combined the conventional ISM method with the neutrosophic theory known as – Neutrosophic ISM. Using the neutrosophic ISM, the driving and dependence power and hierarchical relationship of the barriers to assessing their direct and indirect effect while implementing CE-ST is determined. Further, the remained manuscript is organized in the following sections. The extensive review of literature on CE, ST, and textile and apparel industries is provided in section 2. Section 3 illustrates the detailed Neutrosophic ISM methodology adopted for conducting the research work. Section 4 describes the results and analysis. Where Section 5 presents the findings. Section 6 outlined the research implications and contributions of the present study. The concluding remarks, limitations, and future research directions are provided in section 7.

2 Literature Review

A comprehensive review of the existing body of knowledge to gain insights into the essence of and barriers to the adoption of CE and ST in TAI is conducted. The recently published literature from 2015-2022 is reviewed to ensure the collection of the latest articles for aligning the present study with the current trend of research. The published literature is categorized into four sub-sections, namely - (1) CE in TAI, (2) Smart Technology adoption in TAI, (3) Barriers in implementing CE-ST in TAI, and (4) Tools and techniques used for analysis.

2.1 Circular Economy in Textile and Apparel Industry

The circular economy is one of the widely discussed topics of the present era that has attracted massive attention from the industry and academia domains (N. Kumar et al., 2022; Mishra et al., 2022). Manufacturing industries are trying to formulate novel strategies to transform their operations and supply chains in more sustainable ways to gain the benefits of sustainability as a competitive priority (Dohale, Gunasekaran, Akarte, & Verma, 2022) by successfully implementing CE. Kirchherr et al. (2017) provided an elaborative definition of CE as –

> *"…. A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations …."*

The role of CE in different industries, viz. automotive, apparel, construction, electronic, agriculture, etc. to attain sustainable advantage is critical. The textile and apparel industry is one of the biggest sectors and accounted for a global market worth over US$ 1.5 trillion in 2020 and is expected to grow to US$ 2.25 trillion by 2025 (Shahbandeh 2021). However, TAI is one of the most polluting sectors. The major negative impacts on the environment associated with the TAI products are typically related to energy consumption while producing man-made yarns, water and harmful chemicals consumption, massive CO2 emissions, and solid wastes, which directly impact the ecological system (Dohale, Ambilkar, Kumar, Mangla, et al. 2023; Muthu 2017; Resta et al. 2016). Most of the textiles in the world are produced in the UK and Netherlands. Out of the total waste collected from TAI within the UK and Netherlands, approximately 61% of the waste ends up in landfills or is incinerated, thereby creating a massive harmful impact on sustainability (Muthu 2019). From the remaining 39% of waste, 84% is reused, while the remaining 16% undergoes recycling. In the USA, about 85% of post-consumer textile waste (PCTW) is landfilled each year (Harmony 2015). At the same time, emerging economies, like India, also has around 73% of PCTW landfilled (Zachariah 2020). The estimates of the textile waste for china are more than 20 million tons, which is double the USA and EU (Ütebay et al. 2020), and the TAI in china disposes over 2.5 billion tons of wastewater each year, thereby creating hazardous environmental impacts (EDGE 2020).

To overcome these difficulties associated with TAI waste, Government bodies from different countries have started initiatives to adopt CE practices. For example, the UK government has started the 'Circular Economy Package (CEP)' to reduce waste and developed the 'Resources and Waste Strategy (RWS)' for England to maintain a better state of the environment. Scottish government in 2016 initiated a circular economy strategy entitled 'Making Things Last'. The Department of Agriculture, Environment & Rural Affairs (DAERA) - Ireland launched an "Environment Strategy for Northern Ireland" which considers environmental priorities and manages sustainability. The United States inducted sustainable goals, including "Responsible Consumption and Production", "Clean Water and Sanitation", and "Climate Action" (Cai and Choi 2020). The US Environmental Protection Agency has introduced policies, such as the 'State of the Circular Economy in America' to promote CE. Apart from the developed countries, many developing countries have started sustainability and circular economy policies. The Chinese government has inducted the circular economy (CE) on different fronts, such as - legislation, policy reform, pilot projects, and monitoring and evaluation activities to overcome the environmental impact (Pesce et al. 2020; World Bank 2009) and constructed eco-industrial parks to promote the green awareness in industrial supply chains by providing innovative CE practices (Zhu et al. 2011). Recently, the initiative *'Atmanirbhar Bharat'* launched by the Government of India in 2020 is a key move towards sustainable growth and an economical approach to eliminate waste by implementing CE strategies (NITI Aayog 2021). Further, the 'Swachh *Bharat'* movement launched in 2016 attempts to reduce wastes disposed in environment to maintain sustainability and ecology (Fiksel et al. 2021).

2.2 Smart Technologies Adoption in Textile and Apparel Industries

Although the conclusive definition of industry 4.0 is unaddressed, the global manufacturing sector has been preparing itself to adopt smart technologies since the emergence of the fourth industrial revolution, Industry 4.0 (Dohale, Akarte, et al. 2022; Kamble et al. 2018; Majumdar, Garg, et al. 2021). Smart technologies, namely industrial internet of things (IIoT), blockchain, big data analytics (BDA), virtual reality (VR), 3D printing (3DP), cloud computing (CC), cyber-physical systems (CPS), etc. are the central pillars of industry 4.0 implementation (Dohale, Verma, Gunasekaran, and Akarte 2023; Frank et al. 2019; Kamble et al. 2018). The manufacturing sector is on the brink of implementing smart technologies most suitable for their operationalization.

The textile sector has determined the potential of these smart technologies and is gaining massive interest in implementing industry 4.0. These technologies have offered new paradigms to overcome the challenges within successful TAI operations (Majumdar, Garg, et al. 2021). TAI has started utilizing a few smart technologies (as mentioned in Section 1), such as blockchain, virtual reality, etc. Further, in recent, TAI has utilized the 3DP to create more sustainable clothes and utilize CE principles (Hohn and Durach 2021; Keefe et al. 2022; Sitotaw et al. 2020). To give some examples - Julia Daviy, a well-known fashion designer using 3DP technology, created biodegradable and recyclable fashion apparel (Wardini 2020). 'VIP Tie 3D' produces Stylish Ties using 3DP technology (Sculpteo 2021). The Ministry of supply produces 3D-printed knit blazers and safety masks (Ministry of Supply 2020). The major benefits of using 3DP in producing clothes, apart from reducing environmental impacts, include – Quicker to market products, high customization, minimum inventory, fully recyclable clothing, etc. (Wardini 2020). Apart from 3DP, TAI started implementing IoT to retain the benefits, such as – smart garments, E-commerce, smart clothing and wearables, complete monitoring, etc. (Fernández-Caramés and Fraga-Lamas 2018).

The Government of India launched the 'Digital India' program in 2015 to promote smart technology adoption for creating smart production and service facilities, smart infrastructure, smart societies, and smart education systems (Digital India 2015). The GOI further initiates the "Make in India" movement with the objective of promoting the Indian textile and apparel manufacturers to become smart and sustainable to create a circular value chain and ecosystem (Kamble et al. 2018; Muthu 2019).

2.3 Barriers to CE-ST implementation in TAI

The interest of the manufacturing sector in implementing CE and ST to reduce the environmental impact of business is rapidly growing. The connectivity associated with the smart technologies of industry 4.0 is capable of providing adequate information about the products through their entire life cycle (Alcayaga et al. 2019). Previous literature reported the role of smart technologies, such as IoT, 3DP, Big Data, Blockchain, etc. in enhancing the sustainable aspects of manufacturing supply chains (Kamble et al. 2018; Majumdar, Sinha, et al. 2021; Papadopoulos et al. 2017; R. D. Raut et al. 2021). However, Liboni et al., (2018) addressed the key barriers, such as – 'cultural aspects', 'economic aspects', and 'technological and legal aspects' that industries encountered while implementing smart industry 4.0 technologies to accomplish the environmental concerns to implement circular strategies of reuse, remanufacturing and recycling. Majumdar et al. (2021) pointed out that barriers, namely ‘high implementation cost’, ‘fear of failure’, and ‘seamless integration and compatibility issues’ are the crucial challenges apparel industries witness while implementing industry 4.0 technologies. Kamble et al. (2018) reported that ‘legal and contractual uncertainty’ is the key barrier for the Indian manufacturing sector to implement Industry 4.0 and thereby enjoy the benefits of enhanced manufacturing performance through smart technology adoption. Majumdar et al., (2021b) identified the green supply chain (GSC) risks in apparel industries and found that ‘financial and business environment risk’ significantly impacts GSC and ‘supply risks’, ‘demand risks’, and ‘process risks’ are frequently occuring in GSC. Majumdar and Sinha (2019) determined that ‘lack of consumer support and encouragement’, ‘lack of guidance and support from regulatory authorities’ and ‘high implementation and maintenance cost’ are critical barriers for GSC in textile industries of Southeast Asia. In the present research work, the barriers to CE-ST implementation through a comprehensive review of literature are identified and enlisted in Appendix A1.

2.4 Tools and Techniques to model the barriers to CE-ST implementation in TAI

In the existing body of knowledge, to highlight the challenges within TAI by analyzing the factors, risks, and barriers related to CE-ST implementation, multi-criteria decision-making (MCDM) techniques are widely used. The tools and research methods deployed in the previous studies related to CE-ST and TAI are detailed in Table 1.

Table 1. Tools and Techniques to model CE-ST barriers

Authors	Contribution	Research Tool	Research Context
(Gardas et al. 2018)	Identification of challenges to sustainability and cause and effect relationship amongst theme	Fuzzy Delphi - DEMATEL	Sustainability and Textile and Apparel industry
(Majumdar, Garg, et al. 2021)	Identification of barriers and determination of inter-relationship between them	ISM	Industry 4.0 and Textile and clothing industry
(Majumdar, Sinha, et al. 2021)	Identification of the risks and risk prioritization	Fuzzy AHP	Green supply chain and clothing industry
(Majumdar and Sinha 2019)	Identification of barriers and interrelationships between them	ISM	Green supply chain and textile industry
(Adhikari and Bisi 2020)	Computed collaboration, bargaining, and fairness aspects	Mathematical Modeling	Green supply chain and Apparel Industry
(Cai and Choi 2020)	Identification of sustainable development goals	Systematic Literature Review	Green apparel supply chains

Authors	Contribution	Research Tool	Research Context
(R. Raut et al. 2019)	Identification of barriers and interrelationships between them	ISM-MICMAC	Sustainable Supply Chain and Textile and apparel industries
(Huang et al. 2021)	Identification of barriers and interrelationships between them	Fuzzy Delphi-TISM-MICMAC	Circular Economy and Textile industry
(Tumpa et al. 2019)	Identification and analysis of barriers	Hierarchical Cluster analysis	Green supply chain in Textile industry
(Kazancoglu et al. 2020)	Barriers identification and Development of Conceptual Framework	Conceptual	Circular Economy and Textile Industry
(Jia et al. 2020)	Identification of drivers, barriers, practices, and indicators	Systematic Literature Review	CE and TAI

2.5 Research Gaps

As evident from the extensive literature review, it was observed that CE-ST would have immense potential to make a significant revolution in TAI. However, there is a critical need to develop a foundationary work to implement CE-ST. Several research gaps (RG) in the literature review are determined and discussed next.

RG 1. The literature has widely reported the contributions related to CE or ST (Industry 4.0) in TAI. However, the combined review of CE-ST is missing in the literature. So it is crucial to highlight the influence of implementing CE-ST in the Textile and apparel industry (Ahmad et al. 2020) by determining the novel barriers within TAI.

RG 2. The adoption of ST of Industry 4.0 and sustainable SC of CE has minimized the challenges for an automobile organization (G. Yadav et al. 2020) as these two approaches, i.e. ST-CE, complement each other. This justification offers the opportunity to explore the integration of CE-ST in TAI.

RG 3. The emergence of the novel concept of smart circular technology (SCT) (Alcayaga et al. 2019) has triggered research opportunities for academia to develop qualitative and quantitative models to analyze the barriers, enablers, and crucial factors that have an impact on the implementation of SCT in TAI, as TAI is transforming to Textile 4.0 (Braglia et al. 2020; Ramaiah 2021).

RG 4. As evident from Table 2, the traditional methodologies are typically used to determine the barriers and their interrelationship. Literature is sparse to develop a new method or modify the existing methods to overcome this challenge.

The aforementioned gaps posed a critical need to identify and define barriers to implementing CE-ST for TAI in emerging economies like India, evaluate the interrelation between the barriers, and determine significant strategies to mitigate the critical barriers.

3 Research Methodology

The proposed methodology comprises three stages to analyze the barriers to the implementation of CE-ST in TAI. The first stage of the methodology comprises the identification of the barriers using existing literature. Further, the identified barriers are verified through a validatory survey to determine the essential and relevant barriers influencing CE-ST implementation in TAI. In the second stage, the ISM method is deployed to develop the hierarchical model of the barriers, which helps determine the contextual interrelationship between the verified barriers. Finally, in the third stage, this study combines the ISM with the neutrosophic approach, i.e. Neutrosophic ISM, to get individual responses from the industry experts. Further, the neutrosophic responses are combined to compute the driving and dependence power of the barriers for determining the critical barriers to CE-ST adoption in TAI. Fig. 1 illustrates the detailed roadmap for the proposed research methodology.

3.1 Identification and Validation of CE-ST Barriers

Initially, a comprehensive literature review is conducted to determine the barriers that influence CE-ST adoption in TAI. The complete details of the identified barriers are provided in Appendix A1. Thereafter, a validatory survey is carried out to verify the CE-ST barriers using industry experts. The rationale for selecting the validatory survey technique in this study is that it has the potential to utilize a maximum number of experts to verify the phenomena under study (Majumdar, Garg, et al. 2021). A list of 110 textile and apparel industries is identified from the Confederation of Indian Textile Industry (CITI) database to conduct a validatory survey. The Chief Technical Officers (CTOs), Directors, Environmental Manager, Production Manager, and the IT managers of these firms are contacted. Further, to academically verify the significance of the CE-ST barriers, the expertise of 16 renowned academicians working in a combined 'circular economy and industry 4.0 (smart technology)' domain was utilized. In this manner, 126 experts were contacted to validate the CE-ST barriers. The contacted experts were asked to assign scores to the identified barriers based on their relevance to CE-ST implementation using the five-point Likert scale (Strongly Disagree = 1; Strongly agree = 5). The 126 experts were asked to provide their responses within five weeks timeframe; 82 responses were received from industry experts, while all 16 academic experts responded. In this manner, 98 responses were received, making the response rate 77.77%. In previous studies, researchers mentioned that a response rate higher than 20% is suitable for gaining valuable insights into the problem through surveyed data (Majumdar, Sinha, et al. 2021; Malhotra and Grover 1998). The analysis of experts' profiles depicts that 26.53% respondents had a Ph.D. (doctorate) degree. The post-graduate respondents are the most with 54.08% contribution. While 19.38% of respondents are observed to have a graduate degree. The profile of the participants is provided in Appendix A2 and A3. The details of the questionnaire and responses are provided in the supplementary file.

Barriers having a mean score of 3.0 and above are considered relevant for further analysis (Majumdar, Garg, et al. 2021; Majumdar, Sinha, et al. 2021). Thus, the final set includes 11 barriers, namely - unawareness about CE-ST adoption (B1), unavailability of generic framework (B2), unavailability of skilled resources (B3), lack of digital infrastructure (B4), lack of capability and motivation (B5), lack of government support and subsidies (B6), lack of knowledge about CE practices (B7), unawareness of adoption policies (B8), lack of acceptability (B9), lack of circular SC design aspects (B10), resistance for cultural change (B11). These verified 11 barriers are considered for further analysis using Neutrosophic ISM.

3.2 Neutrosophic Interpretive Structural Modeling

Interpretive Structural Modeling (ISM) is conceived by Warfield (1974) to create a structural model of the system under study to simplify it (Sushil 2020). ISM helps determine the direct and indirect relationships between the factors affecting the system under consideration. ISM utilizes expert opinions for identifying the contextual inter-relationship between the various factors influencing the system. ISM has additive advantages over the analytical hierarchy process and analytical network process of capturing ‘what’ and ‘how’ phenomenon and provides insights about the “leads to” relationship between factors in real-life problems. Despite the advantages, ISM comprises major shortcomings, such as – 1) It uses a binary scale to measure the influence of one criterion over the other (1- Influence, 0- No Influence), due to which the judgment comprises vagueness and subjectivity. 2) It lacks to answer the ‘why’ phenomenon 3) It purely relies on the consensus vote method, in which the accuracy in judgment may be impacted due to influenced personalities or the senior-level expert, group pressure, etc. Due to these reasons, the other forms of ISM, such as TISM and Fuzzy ISM are coined. However, in every form, some drawbacks are observed (refer Table 2).

In this study, we deployed a novel form of ISM comprising the combination of traditional ISM with the neutrosophic approach, termed as - Neutrosophic ISM (Dohale, Ambilkar, Gunasekaran, and Bilolikar 2022; Dohale, Ambilkar, Kumar, Mangla, et al. 2023). A detailed comparison of all the forms of ISM is enlisted in Table 2. The rationale for selecting the neutrosophic approach is its ability to deal with uncertainties and inconsistencies in decision-making (Nabeeh et al. 2019). Unlike fuzzy sets, it effectively handles indeterminant cases (Nabeeh et al. 2021). Neutrosophic approach effectively computes indeterminacy within decision-makers' perceptions (Abdel-Baset et al. 2019). Neutrosophic approach aids in avoiding unclear, vague, and inexact judgments of experts (Ambilkar et al. 2023).

Table 2. Evaluation of ISM's different forms (Dohale, Ambilkar, Gunasekaran, and Bilolikar 2022)

Type of ISM	Benefits	Drawbacks
Classical ISM	• Helps to characterize the relationships between several criteria • Helps to determine the impacts of criteria on each other • Helps to depict an intricate system in a simplified way • Helps to identify the structure of the influential aspects in a system typically in a hierarchical way, i.e. digraph • Helps to evaluate the driving and dependence power of aspects • Helps to explain the "what" and "how" characteristics of system	• This method only uses the binary scale to measure the influence • This method fails to compute the low, medium, high, etc. levels of influence • This method fails to handle imprecise and vague information • This method is unable to answer the "why" aspects (which helps in theory building) • This method comprises drawbacks like using a Consensus vote method to aggregate the experts' opinions
Total ISM (TISM)	• This method includes all the benefits of ISM • This method also attempts to answer the "why" phenomenon	• This method uses a binary scale to measure the influence • This method fails to compute the level of influence • This method fails to handle imprecise and vague information, which usually exists in real cases • This method uses the consensus vote method to aggregate the experts' opinions
Fuzzy ISM	• This method includes all the benefits of classical ISM • This method efficiently handles the inaccurate, unclear, or vague nature through one-grade membership degree • This method illustrates the preference judgment values of the decision-maker effectively • The level of influence can be computed by this method	Identified the following drawbacks in Fuzzy ISM, which are not yet addressed in the existing literature. • The experts' opinions are aggregated using the consensus vote method • Unable to incorporate the membership degrees, namely – 'truth, indeterminacy, and falsity' degrees • Difficult to Compute transitivity
Neutrosophic ISM	• Comprises all the benefits of ISM, TISM, Fuzzy ISM • This method also describes the preference of the decision-maker effectively • This method enriches decision-making with holistic insights • This method effectively handles vagueness and uncertainty than other ISMs, due to the consideration of three different grades- "truth, indeterminacy, and falsity degree" • This method points out how to enhance inconsistent judgments • The widely used and mathematically sound geometric mean approach is used by this method to aggregate the judgments of several experts	• Requires more computation time in calculating driving and dependence power in comparison with other forms of ISM

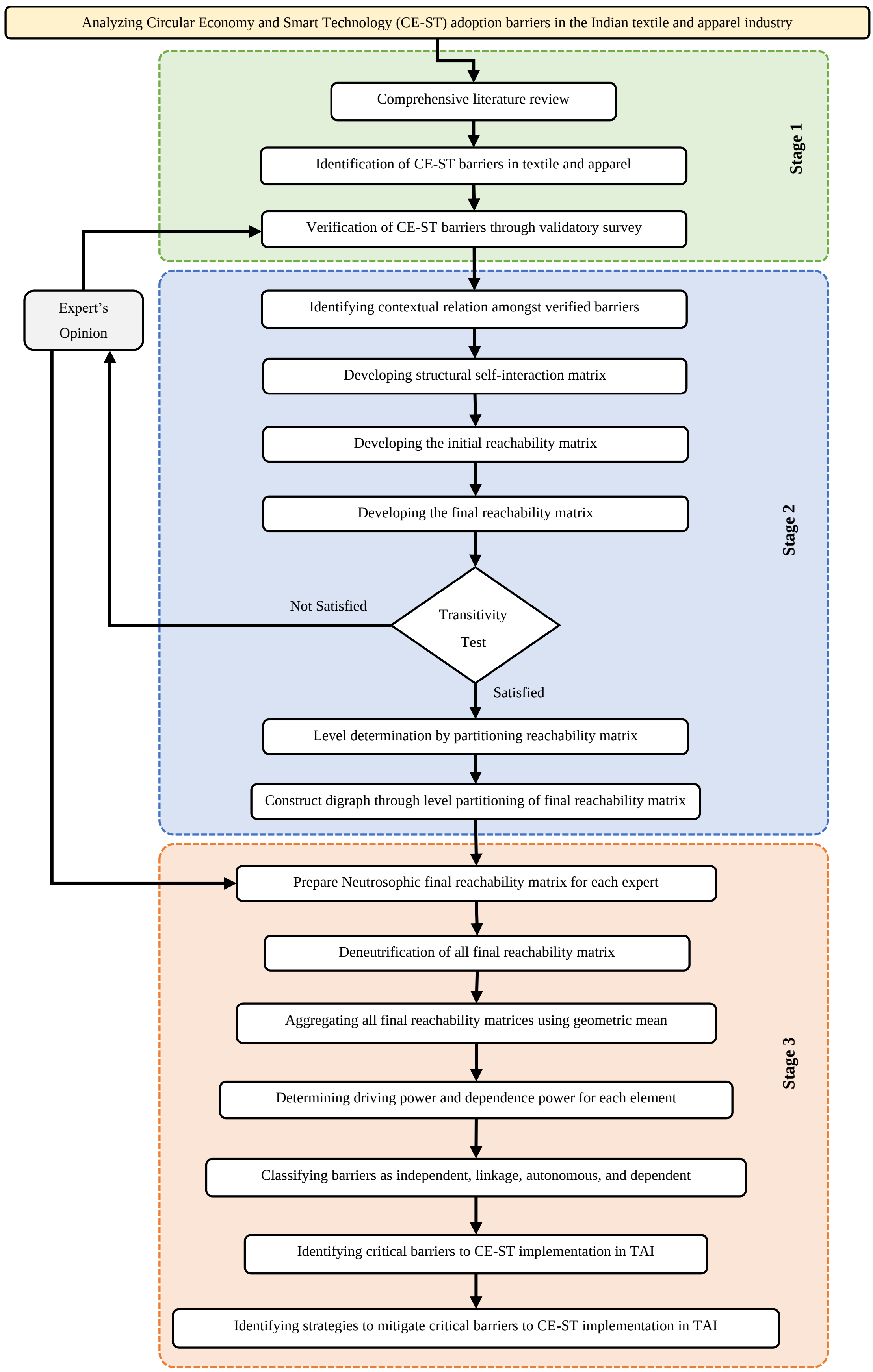

Fig. 1. Research Methodology

3.3 Definitions of Neutrosophic sets

The strength of a neutrosophic set lies in its ability to handle inconsistent and vague data by studying the level of truth, indeterminate, and false degrees of the data (Broumi et al. 2020; Nabeeh et al. 2019). Literature has provided the critical definitions of neutrosophic sets, single-valued neutrosophic sets, triangular neutrosophic sets, and trapezoidal neutrosophic sets (Abdel-Basset et al. 2018; Broumi et al. 2020; Pamucar et al. 2020). The definitions are discussed next.

Definition 1: Neutrosophic Set

Let X be a space of points, $x \in X$. The neutrosophic set P characterized by three membership functions which are a truth-membership function $T_P(x)$, an indeterminacy-membership function $I_P(x)$, and falsity-membership function $F_P(x)$. Where, $T_P(x)$, $I_P(x)$ and $F_P(x)$ are real standard or real non-standard subsets of]−0,1+[. That is for $T_P(x),\ I_P(x)\ and\ \ F_P(x): X \rightarrow]^{-}0, 1^{+}[$. Also, the sum operator of $T_P(x)$, $I_P(x)$ and $F_P(x)$ has no restrictions. Therefore, $0- \leq supT_P(x) + sup\ I_P(x) + sup\ F_P(x) \leq 3^{+}$.

Definition 2: Single Valued Neutrosophic Number (SVN)

Let X be a universe of discourse. A single-valued neutrosophic (SVN) set P over X is an object taking the form as $X = \{\langle x, T_P(x), I_P(x), F_P(x)\rangle : x \in X\}$, where $T_P(x),\ I_P(x), and\ \ F_P(x): X \rightarrow [0,1]\ with\ 0 \leq T_P(x) + I_P(x) + F_P(x) \leq 3\ for\ all\ x \in X$. For convenience, the SVN number is typified by $P = (p, q, r), where\ p, q, r \in [0,1]$ and $p + q + r \leq 3$.

Definition 3: Single Valued Triangular Neutrosophic Number (SVTN)

Suppose $\alpha_{\tilde{p}}, \theta_{\tilde{p}}, \beta_{\tilde{p}} \in [0,1]$ and $p_1, p_2, p_3 \in M$ where $p_1 \leq p_2 \leq p_3$. Then, a triangular neutrosophic (SVTN) number, $\tilde{p} = \langle (p_1, p_2, p_3); \alpha_{\tilde{p}}, \theta_{\tilde{p}}, \beta_{\tilde{p}} \rangle$ is a neutrosophic set on the real line set M. The truth-membership, indeterminacy-membership, and falsity-membership functions of the SVTN number are defined as:

$$T_{\tilde{p}}(x) = \begin{cases} \alpha_{\tilde{p}} \dfrac{(x - p_1)}{(p_2 - p_1)} & (p_1 \leq x \leq p_2) \\ \alpha_{\tilde{p}} & (x = p_2) \\ 0 & otherwise, \end{cases} \quad (1)$$

$$I_{\tilde{p}}(x) = \begin{cases} \dfrac{\left((p_2 - x) + \theta_{\tilde{p}}(x - p_1)\right)}{(p_2 - p_1)} & (p_1 \leq x \leq p_2) \\ \theta_{\tilde{p}} & (x = p_2) \\ 1 & otherwise, \end{cases} \quad (2)$$

$$F_{\tilde{p}}(x) = \begin{cases} \dfrac{\left((p_2 - x) + \beta_{\tilde{p}}(x - p_1)\right)}{(p_2 - p_1)} & (p_1 \le x \le p_2) \\ \beta_{\tilde{p}} & (x = p_2) \\ \dfrac{\left((x - p_2) + \beta_{\tilde{p}}(p_3 - x)\right)}{(p_3 - p_2)} & (p_2 \le x \le p_3) \end{cases} \quad (3)$$

Where, $\alpha_{\tilde{p}}, \theta_{\tilde{p}}$ *and* $\beta_{\tilde{p}}$ represents the maximum degree of truth-membership, the minimum degree of indeterminacy-membership, and the minimum falsity-memberships degree, respectively. SVTN number $\tilde{p} = \langle (p_1, p_2, p_3); \alpha_{\tilde{p}}, \theta_{\tilde{p}}, \beta_{\tilde{p}} \rangle$ may express an ill-defined quantity of the range, which is approximately equal to the interval $[p_2, p_3]$.

Definition 4: Single Valued Trapezoidal Neutrosophic Number (SVTrNN)

A single-valued trapezoidal neutrosophic number (SVTrNN) is represented as $\tilde{p} = \langle (p_1, p_2, p_3, p_4), (q_1, q_2, q_3, q_4), (r_1, r_2, r_3, r_4) \rangle$. The SVTrNN parameters satisfy the following condition: $(p_1 \le p_2 \le p_3 \le p_4)$, $(q_1 \le q_2 \le q_3 \le q_4)$, $(r_1 \le r_2 \le r_3 \le r_4)$ (Pamucar et al. 2020). Then, the truth $(T_{\tilde{p}}(x))$, indeterminacy $(I_{\tilde{p}}(x))$, and falsity $(F_{\tilde{p}}(x))$ membership degrees can be represented in following manner.

$$T_{\tilde{p}}(x) = \begin{cases} \dfrac{(x - p_1)}{(p_2 - p_1)}, & (p_1 \le x \le p_2) \\ 1, & (p_2 \le x \le p_3) \\ \dfrac{(p_4 - x)}{(p_4 - p_3)}, & (p_3 \le x \le p_4) \\ 0, & Otherwise \end{cases} \quad (4)$$

$$I_{\tilde{p}}(x) = \begin{cases} \dfrac{(x - q_1)}{(q_2 - q_1)}, & (q_1 \le x \le q_2) \\ 1, & (q_2 \le x \le q_3) \\ \dfrac{(q_4 - x)}{(q_4 - q_3)}, & (q_3 \le x \le q_4) \\ 0, & Otherwise \end{cases} \quad (5)$$

$$F_{\tilde{p}}(x) = \begin{cases} \dfrac{(x - r_1)}{(r_2 - r_1)}, & (r_1 \le x \le r_2) \\ 1, & (r_2 \le x \le r_3) \\ \dfrac{(r_4 - x)}{(r_4 - r_3)}, & (r_3 \le x \le r_4) \\ 0, & Otherwise \end{cases} \quad (6)$$

This study adopted trapezoidal neutrosophic numbers due to their advantages over others. The advantages of SVTrNN are discussed next.

3.4 Advantages of SVTrNN

According to Broumi et al. (2020) and Pamucar et al. (2020), the advantages of SVTrNN are:

- The SVTrNN represents a single and triangular neutrosophic number in a generalized manner.
- The SVTrNN is arithmetically suitable for expressing opinions because it is widely distributed over any scale.
- The SVTrNN is represented in three independent membership degrees, i.e., truth, indeterminacy, and falsity.
- The SVTrNN is more effective in expressing neutrosophic information than other neutrosophic forms.

Thus, the SVTrNN is appropriate for calculating neutrosophic multiple attribute decision-making problems (Broumi et al. 2020).

3.5 Neutrosophic ISM Computation Process

In this section, the main steps for the computation of the barriers using the neutrosophic ISM framework are presented with a detailed description.

3.5.1 Step 1: Develop a Structural Self Interaction Matrix

Develop a pairwise comparison matrix, i.e. a structural self-interaction matrix (SSIM) based on the contextual relationship amongst the 11 CE-ST barriers using experts' opinions. The relationship between factors can be expressed in terms of four symbols as follows-

V: depicts attribute i aids in achieving attribute j;

A: depicts attribute j aids in achieving attribute i;

X: depicts attributes i and j aids in achieving each other; and

O: depicts no relationship amongst attributes i and j.

The number of experts required for developing SSIM and conducting ISM and N-ISM ranges between 5 and 15 experts to maintain adequate and precise results (Dohale, Ambilkar, Gunasekaran, and Bilolikar 2022). We evaluated the experts based on the three criteria - 1) Experts should have knowledge of Smart technology and Circular economy practices and an experience in the topic of investigation (minimum ten years of experience); 2) Expert’s working position within the organization; and 3) Experts should be available and willing to participate in the study (Bokrantz et al. 2017; Dohale et al. 2021). Initially, 25 experts from the apparel and textile industries falling under the above-mentioned criteria were contacted. Out of 25, 8 experts have shown their interest and willingly participated in the study for conducting neutrosophic ISM. The detailed profile of the eight industry experts is provided in Appendix A3. All the responses related to SSIM from the eight experts are gathered and correlated. The final SSIM is developed based on the highest frequency assigned to V, A, X, and O (Chirra and Kumar 2018). For example - in any pairwise comparison between barrier i and barrier j, the responses from eight experts received as – 4 experts provided V, 1 expert provided A, 3 experts provided X, and no experts with O, in this condition being V has the highest frequency, it is considered in the final SSIM. If the same frequency gets assigned to V, A, X, or O, then that comparison is reinitiated until a clear high-frequency-based judgment is received (Chirra and Kumar 2018). After conducting this iterative process, a final SSIM is prepared, as shown in Table 3.

Table 3. Structural Self Interaction Matrix (SSIM)

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
B1	1	O	V	V	A	A	V	V	V	V	V
B2		1	O	O	O	A	V	A	V	V	O
B3			1	O	A	A	V	A	V	X	A
B4				1	V	A	V	A	V	O	O
B5					1	O	X	A	X	A	V
B6						1	V	V	V	V	V
B7							1	A	X	A	A
B8								1	V	V	V
B9									1	A	A
B10										1	O
B11											1

3.5.2 Step 2: Develop an Initial Reachability Matrix

The values 1 and 0 are substituted in the SSIM by replacing V, A, X, and O to get the initial reachability matrix, as shown in Table 4. To replace V, A, X, and O with values 1 and 0, following rules are considered (Kamble et al. 2018; Warfield 1974).

- If in the SSIM, the relation of (i, j) is defined using V, then the (i, j) is replaced by 1, while the (j, i) is replaced by 0.
- If in the SSIM, the relation of (i, j) is defined using A, then the (i, j) is replaced by 0, and the (j, i) is replaced by 1.
- If in the SSIM, the relation of (i, j) is defined using X, then the (i, j) and the (j, i) are replaced by 1.
- If in the SSIM, the relation of (i, j) is defined using O, then the (i, j) and (j, i) are replaced by 0.

3.5.3 Step 3: Develop a Final Reachability Matrix

In this step, a final reachability matrix is developed by using a transitivity check. Transitivity includes a theory of sets comprising Boolean multiplication and addition (Kumar et al. 2021). According to the transitivity concept: if entity "i" is related to entity "j", and entity "j" is related to entity "k," then entity "i" must be related to entity "k" (R. Raut et al. 2019; Singh et al. 2007). It aids in managing the consistency within the matrix (Majumdar, Garg, et al. 2021; Singh et al. 2007). The final reachability matrix is developed using the transitivity concept, as shown in Table 5.

Table 4. Initial reachability Matrix

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
B1	1	0	1	1	0	0	1	1	1	1	1
B2	0	1	0	0	0	0	1	0	1	1	0
B3	0	0	1	0	1	0	1	0	1	1	0
B4	0	0	0	1	1	0	1	0	1	0	0
B5	1	0	0	0	1	0	1	0	1	0	1
B6	1	0	1	1	1	1	1	1	1	1	1
B7	0	0	0	0	1	0	1	0	1	0	0
B8	0	1	1	1	1	0	1	1	1	1	1
B9	0	0	0	0	1	0	1	0	1	0	0
B10	0	1	0	0	1	0	1	0	1	1	0
B11	0	0	1	0	0	0	1	0	1	0	1

Table 5. Final Reachability Matrix

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
B1	1	1*	1	1	1*	0	1	1	1	1	1
B2	0	1	0	0	1*	0	1	0	1	1	0
B3	0	1*	1	0	1	0	1	0	1	1	0
B4	1*	0	0	1	1	0	1	0	1	0	0
B5	1	0	1*	0	1	0	1	1*	1	1*	1
B6	1	1*	1	1	1	1	1	1	1	1	1
B7	1*	0	0	0	1	0	1	0	1	0	0
B8	1*	1	1	1	1	0	1	1	1	1	1
B9	1*	0	0	0	1	0	1	0	1	0	0
B10	1*	1	0	0	1	0	1	0	1	1	0
B11	0	0	1	0	1*	1*	1	0	1	1*	1

(Note: The values marked with * indicate transitivity)

3.5.4 Step 4: Level Partitioning

The final reachability matrix is used to determine the reachability sets and antecedent sets for each barrier considered in this study. The reachability set for any barrier comprises other barriers that are having value '1' and present in the row, including the barrier itself. Whereas the antecedent set for a barrier comprises any barriers that are having value ‘1’ and present in the column, including the barrier itself. Further, the interaction set is determined for all barriers. Any barriers having the same reachability and intersection sets are placed on the top level in the ISM digraph. The barriers retaining the top position are separated from the list, and the same procedure is repeated to determine the position of the other barriers. Table 6 provides the details about the reachability, antecedent, and interaction sets for all the barriers.

Table 6. Level Partitioning

Barriers	**Reachability set**	**Antecedent set**	**Intersection Set**	**Level**
B1	B1, B8	B1, B6, B8	B1, B8	VI
B2	B2	B1, B2, B3, B6, B8	B2	III
B3	B3	B1, B3, B6, B8, B11	B3	IV
B4	B1, B4	B1, B4, B6, B8	B1, B4	III
B5	B1, B3, B5, B7, B8, B9, B10, B11	B1, B2, B3, B4, B5, B6, B7, B8, B9, B10, B11	B1, B3, B5, B7, B8, B9, B10, B11	I
B6	B6	B6	B6	VII
B7	B1, B5, B7, B9	B1, B2, B3, B4, B5, B6, B7, B8, B9, B10, B11	B1, B5, B7, B9	I
B8	B1, B8	B1, B6, B8	B1, B8	VI
B9	B5, B7, B9	B1, B2, B3, B4, B5, B6, B7, B8, B9, B10, B11	B5, B7, B9	I
B10	B1, B2, B10	B1, B2, B3, B6, B8, B10, B11	B1, B2, B10	II
B11	B11	B1, B6, B8, B11	B11	V

3.5.5 Step 5: Constructing a Diagraph

A digraph is a model in hierarchical form constructed through the level partitioning of the final reachability matrix. As explained earlier, the barrier retaining top position is placed at the top of the digraph. Further, the barriers retaining the second position are placed in the next levels. The process is repeated until all barriers are placed in a digraph. The digraph constructed in the present study is shown in Fig.2.

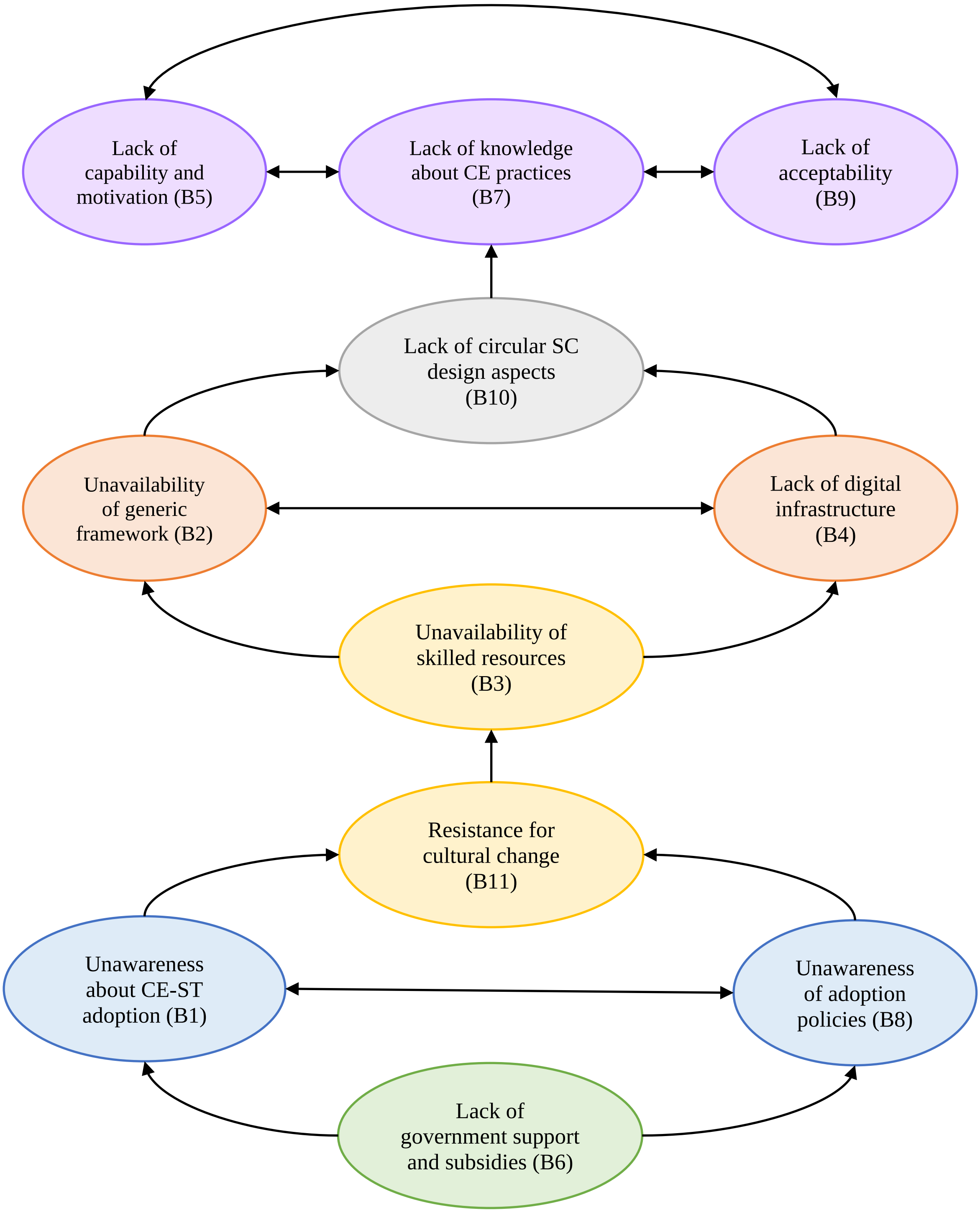

Fig. 2. Diagraph of CE-ST barriers in TAI

3.5.6 Step 6: Determining the Driving and Dependence Power of the barriers

In ISM, the relationship between two attributes is represented by: 0 for no influence and 1 for influence. However, in real-life situations, the influence can be represented as - absolutely high influence, low influence, medium influence, etc. Thus, to match the real-life ambiance, this study evaluated the influence using a seven-point trapezoidal neutrosophic scale, as shown in Table 7.

All eight experts are asked to rate the level of influence between the barriers based on the seven-point neutrosophic scale shown in Table 7. Thus, the final reachability matrix shown in Table 5 is modified to the neutrosophic reachability matrix. The value '1' in Table 5, showing the influence between the barriers, is replaced with the linguistic terms provided in Table 7. All eight experts provided their individual judgments, thereby creating eight judgment matrices. The sample judgment matrix for Expert-1 demonstrating the level of influence between the barriers using linguistics terms is shown in Table 8.

Table 7. Neutrosophic Seven-Point Scale (Dohale, Ambilkar, Gunasekaran, and Bilolikar 2022)

Linguistic terms	**SVTrNN Number**
Absolutely High (AH)	(0.1,0.1,0.1,0.1), (0.1,0.1,0.1,0.1), (0.1,0.1,0.1,0.1)
High (H)	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)
Fairly High (FH)	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)
Medium (M)	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)
Fairly Low (FL)	(0.5,0.6,0.7,0.8), (0.4,0.6,0.7,0.9), (0.4,0.6,0.7,0.9)
Low (L)	(0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9)
Absolutely Low (AL)	(0.9,0.9,0.9,0.9), (0.9,0.9,0.9,0.9), (0.9,0.9,0.9,0.9)

Table 8. Judgment matrix using neutrosophic linguistic scale for Expert-1

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
B1	1	H	M	M	M	NO	L	L	H	FH	H
B2	NO	1	NO	NO	L	NO	M	NO	H	H	NO
B3	NO	FL	1	NO	L	NO	FL	NO	H	M	NO
B4	M	NO	NO	1	FH	NO	L	NO	FH	NO	NO
B5	H	NO	M	NO	1	NO	FH	M	H	FH	H
B6	M	H	FH	AH	AH	1	FH	FH	AH	H	AH
B7	FH	NO	NO	NO	FL	NO	1	NO	H	NO	NO
B8	M	FL	FL	M	FH	NO	FH	1	H	FL	M
B9	M	NO	NO	NO	L	NO	FL	NO	1	NO	NO
B10	FL	M	NO	NO	H	NO	FL	NO	AH	1	NO
B11	NO	NO	FL	NO	AL	AL	L	NO	FH	AL	1

Once the judgment matrix with the linguistic scale is obtained for individual experts, the linguistics terms are replaced by the respective SVTrNN number, as shown in Table 7, to get a neutrosophic judgment matrix. Thus, eight neutrosophic judgment matrices for each expert are obtained. The sample neutrosophic judgment matrix for expert-1 is provided in Table 9.

After obtaining neutrosophic matrices for all the experts, the denitrification process is conducted to gain crisp values for further analysis. A score function proposed by Pamucar et al. (2020) is utilized to obtain crisp scores from neutrosophic numbers. The score function is given as –

$$S(\tilde{p}) = \frac{1}{3}\left\{2 + \frac{(p_1 + p_2 + p_3 + p_4)}{4} - \frac{(q_1 + q_2 + q_3 + q_4)}{4} - \frac{(r_1 + r_2 + r_3 + r_4)}{4}\right\} \quad (7)$$

After applying equation (7) on the neutrosophic judgment matrices of all experts, the deneutrified judgment matrix will be obtained for all eight experts. The deneutrified matrix for expert-1 is shown in Table 10.

Table 9. Deneutrified Judgement Matrix for Expert-1

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
B1	1.0000	0.6083	0.5167	0.5167	0.5167	0.0000	0.3917	0.3917	0.6083	0.5833	0.6083
B2	0.0000	1.0000	0.0000	0.0000	0.3917	0.0000	0.5167	0.0000	0.6083	0.6083	0.0000
B3	0.0000	0.4500	1.0000	0.0000	0.3917	0.0000	0.4500	0.0000	0.6083	0.5167	0.0000
B4	0.5167	0.0000	0.0000	1.0000	0.5833	0.0000	0.3917	0.0000	0.5833	0.0000	0.0000
B5	0.6083	0.0000	0.5167	0.0000	1.0000	0.0000	0.5833	0.5167	0.6083	0.5833	0.6083
B6	0.5167	0.6083	0.5833	0.6333	0.6333	1.0000	0.5833	0.5833	0.6333	0.6083	0.6333
B7	0.5833	0.0000	0.0000	0.0000	0.4500	0.0000	1.0000	0.0000	0.6083	0.0000	0.0000
B8	0.5167	0.4500	0.4500	0.5167	0.5833	0.0000	0.5833	1.0000	0.6083	0.4500	0.5167
B9	0.5167	0.0000	0.0000	0.0000	0.3917	0.0000	0.4500	0.0000	1.0000	0.0000	0.0000
B10	0.4500	0.5167	0.0000	0.0000	0.6083	0.0000	0.4500	0.0000	0.6333	1.0000	0.0000
B11	0.0000	0.0000	0.4500	0.0000	0.3667	0.3667	0.3917	0.0000	0.5833	0.3667	1.0000

Finally, a geometric mean of deneutrified judgment matrices of all the experts is computed to aggregate the judgments to evaluate the driving and dependence power of each barrier. The geometric mean is a widely used approach to aggregate the judgments. Geometric mean captures the variability associated within the data. Therefore, it is considered the most appropriate method to combine the judgments (Dohale, Ambilkar, Kumar, Mangla, et al. 2023; Hummel et al. 2014). The aggregated judgment matrix is given in Table 11. Further, the CE-ST barriers are classified into four clusters: autonomous, dependent, linkage, and independent, based on the driving and dependence power using a MICMAC (Matrice d’Impacts Croisés

Multiplication Appliqués à un Classement) analysis (Majumdar, Garg, et al. 2021). The cluster diagram of CE-ST barriers is shown in Fig.3.

Table 10. Aggregated Judgement Matrix

Barriers	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**Driving Power**
B1	1.0000	0.5867	0.5078	0.5078	0.5145	0.0000	0.3985	0.4022	0.6020	0.5956	0.5957	**5.7108**
B2	0.0000	1.0000	0.0000	0.0000	0.3917	0.0000	0.5246	0.0000	0.5988	0.6083	0.0000	**3.1234**
B3	0.0000	0.4346	1.0000	0.0000	0.4198	0.0000	0.4346	0.0000	0.6020	0.5167	0.0000	**3.4077**
B4	0.5167	0.0000	0.0000	1.0000	0.5864	0.0000	0.3917	0.0000	0.5833	0.0000	0.0000	**3.0781**
B5	0.6052	0.0000	0.5167	0.0000	1.0000	0.0000	0.5833	0.5167	0.6083	0.5746	0.6082	**5.0129**
B6	0.5156	0.6020	0.5926	0.6333	0.6333	1.0000	0.5833	0.5895	0.6333	0.6052	0.6333	**7.0215**
B7	0.5833	0.0000	0.0000	0.0000	0.4423	0.0000	1.0000	0.0000	0.6083	0.0000	0.0000	**2.6339**
B8	0.5235	0.4500	0.4423	0.5407	0.5833	0.0000	0.5864	1.0000	0.6083	0.4500	0.5246	**5.7091**
B9	0.4905	0.0000	0.0000	0.0000	0.4055	0.0000	0.4500	0.0000	1.0000	0.0000	0.0000	**2.3460**
B10	0.4423	0.5167	0.0000	0.0000	0.6082	0.0000	0.4272	0.0000	0.6302	1.0000	0.0000	**3.6245**
B11	0.0000	0.0000	0.4422	0.0000	0.3697	0.3758	0.4055	0.0000	0.5833	0.3697	1.0000	**3.5463**
Dependence Power	**4.6770**	**3.5900**	**3.5016**	**2.6819**	**5.9547**	**1.3758**	**5.7851**	**2.5083**	**7.0580**	**4.7200**	**3.3618**	**45.2142**

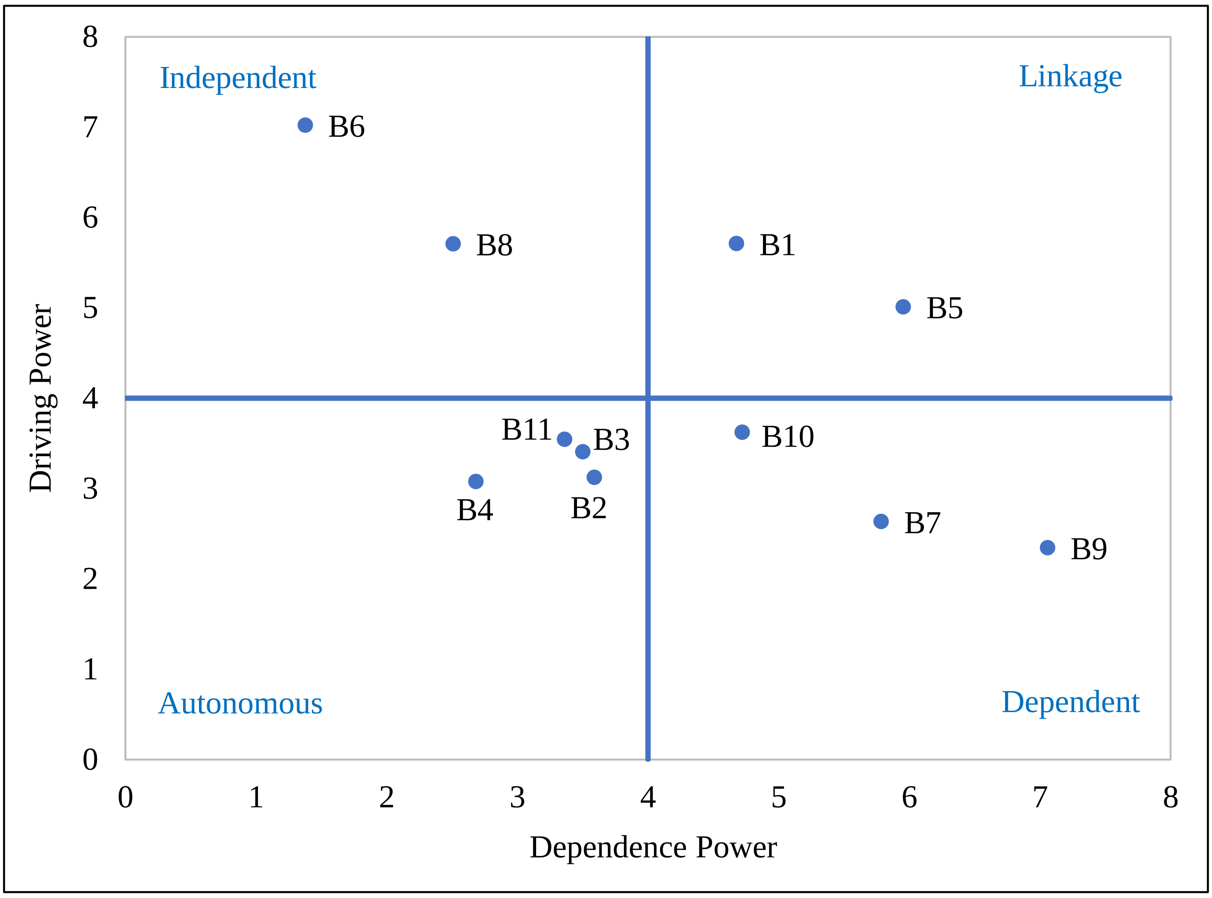

Fig. 3. Cluster Analysis of CE-ST Barriers

Table 11. Neutrosophic Judgement Matrix for Expert-1

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
B1	1	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	0	(0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9)	(0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9)	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)
B2	0	1	0	0	(0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9)	0	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	0	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)	0
B3	0	(0.5,0.6,0.7,0.8), (0.4,0.6,0.7,0.9), (0.4,0.6,0.7,0.9)	1	0	(0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9)	0	(0.5,0.6,0.7,0.8), (0.4,0.6,0.7,0.9), (0.4,0.6,0.7,0.9)	0	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	0
B4	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	0	0	1	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)	0	(0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9)	0	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)	0	0
B5	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)	0	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	0	1	0	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)
B6	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)	(0.1,0.1,0.1,0.1), (0.1,0.1,0.1,0.1), (0.1,0.1,0.1,0.1)	(0.1,0.1,0.1,0.1), (0.1,0.1,0.1,0.1), (0.1,0.1,0.1,0.1)	1	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)	(0.1,0.1,0.1,0.1), (0.1,0.1,0.1,0.1), (0.1,0.1,0.1,0.1)	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)	(0.1,0.1,0.1,0.1), (0.1,0.1,0.1,0.1), (0.1,0.1,0.1,0.1)
B7	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)	0	0	0	(0.5,0.6,0.7,0.8), (0.4,0.6,0.7,0.9), (0.4,0.6,0.7,0.9)	0	1	0	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)	0	0
B8	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	(0.5,0.6,0.7,0.8), (0.4,0.6,0.7,0.9), (0.4,0.6,0.7,0.9)	(0.5,0.6,0.7,0.8), (0.4,0.6,0.7,0.9), (0.4,0.6,0.7,0.9)	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)	0	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)	1	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)	(0.5,0.6,0.7,0.8), (0.4,0.6,0.7,0.9), (0.4,0.6,0.7,0.9)	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)
B9	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	0	0	0	(0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9)	0	(0.5,0.6,0.7,0.8), (0.4,0.6,0.7,0.9), (0.4,0.6,0.7,0.9)	0	1	0	0
B10	(0.5,0.6,0.7,0.8), (0.4,0.6,0.7,0.9), (0.4,0.6,0.7,0.9)	(0.3,0.4,0.5,0.6), (0.2,0.4,0.5,0.7), (0.2,0.4,0.5,0.7)	0	0	(0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3), (0.1,0.1,0.2,0.3)	0	(0.5,0.6,0.7,0.8), (0.4,0.6,0.7,0.9), (0.4,0.6,0.7,0.9)	0	(0.1,0.1,0.1,0.1), (0.1,0.1,0.1,0.1), (0.1,0.1,0.1,0.1)	1	0
B11	0	0	(0.5,0.6,0.7,0.8), (0.4,0.6,0.7,0.9), (0.4,0.6,0.7,0.9)	0	(0.9,0.9,0.9,0.9), (0.9,0.9,0.9,0.9), (0.9,0.9,0.9,0.9)	(0.9,0.9,0.9,0.9), (0.9,0.9,0.9,0.9), (0.9,0.9,0.9,0.9)	(0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9), (0.7,0.8,0.9,0.9)	0	(0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4), (0.1,0.2,0.3,0.4)	(0.9,0.9,0.9,0.9), (0.9,0.9,0.9,0.9), (0.9,0.9,0.9,0.9)	1

4 Results and Analysis

This study manifested the successful implication of a validatory survey followed by a novel neutrosophic ISM technique to analyze the CE-ST adoption barriers in TAI. A total of 11 critical CE-ST barriers are retained for the analysis purpose of this study, which are identified using an extensive literature review and confirmed by a validatory survey technique. The retained 11 CE-ST barriers are further subjected to neurotrophic ISM to determine the interrelationship patterns between the barriers and identify the 'driving and dependence' power, which helps determine the critical barriers.

Based on the level partitioning of the barriers, a digraph of CE-ST adoption barriers in textile and apparel industries is obtained, as shown in Fig. 2. The digraph comprises seven levels. The seven levels are clustered into three groups as - top-level, intermediate, and bottom-level barriers. The bottom-level barriers are those which are highly influential and have a huge impact on other barriers. The digraph depicts – lack of government support and subsidies (B6), unawareness about CE-ST adoption (B1), lack of digital infrastructure (B4), and resistance to cultural change (B11) are the barriers at the bottom level, i.e. level VII, VI and V of a digraph. These barriers drive the intermediate barriers, namely – unavailability of skilled resources (B3), unavailability of generic framework (B2), lack of digital infrastructure (B4), and lack of circular SC design aspects (B10). Whereas lack of acceptability (B9), lack of knowledge about CE practices (B7), and lack of capability and motivation (B5) are the top-level barriers in a digraph. The top-level barriers have the least influence and are largely dependent on the other barriers. The policymakers and Government authorities must focus on the bottom-level barriers to mitigate the problems in adopting CE-ST in TAI. Further, using the driving and dependence power of all the 11 barriers, we classified them into four clusters using a MICMAC analysis as shown in Fig.3. the MICMAC analysis is discussed next.

- **Autonomous barriers:**

  Barriers having lower driving and dependence powers are clustered as autonomous barriers. The barriers in this category have significantly low influence and can be easily tackled. In the present research work, four barriers, namely – unavailability of generic framework (B2), unavailability of skilled resources (human, financial, technical, etc.) (B3), Lack of digital infrastructure (B4), and Resistance for cultural change (B11), are classified as autonomous barriers.

- **Dependent barriers:**

  These barriers are highly dependent on the other barriers and possess high dependence and low driving power. These can be treated as the outcomes an organization is desired to achieve. In this study, the barriers – lack of knowledge about sustainable practices (B7), lack of acceptability (B9), and lack of circular SC design aspects (B10) are found under this cluster. These barriers are largely dependent on the other barriers.
- **Linkage barriers:** The barriers having a high driving and dependence power are called as linkage barriers. The barriers under this category are unstable and can be influenced by other barriers. The fewer linkage barriers make an ISM model stable and robust to replicate in real-life cases (Majumdar and Sinha 2019). Through a MICMAC analysis, two barriers are identified that fall under the linkage type, namely – unawareness about CSC and smart technology adoption (B1) and lack of capability and motivation (B5). The linkage barriers tend to create a feedback effect in the model (A.-Y. Chang et al. 2013) and shall be resolved carefully while implementing the CE-ST in TAI.
- **Independent barriers:** These are the most influential barriers. These barriers possess high driving and low dependence power. Being the major drivers, such barriers require enormous attention from decision-makers. In the present study, lack of government support and subsidies (B6) and unawareness of adoption policies (B8) are induced as the significant independent barriers possessing a strong driving strength in adopting CE-ST in TAI.

5 Discussions of Findings

As evident from the results and analysis, lack of government support and subsidies (B6) has emerged as the critical challenge that restricts CE-ST adoption in TAI. Apart from this, unawareness of adoption policies (B8) and unawareness about CE-ST adoption (B1) shall be critically examined by practitioners and policymakers to implement CE-ST in TAI.

The role of government support in adopting a circular economy and smart industry 4.0 technologies is crucial (Majumdar, Garg, et al. 2021; Muthu 2017). The government shall provide financial support or subsidies to TAI practitioners who desire to adopt CE-ST in their organizations. The adoption of CE is least profitable for many industries due to the price difference between a virgin material which is comparatively lower than the recycled or remanufactured product. Thus, the government shall subsidize CE adoption by providing some incentives to attract more organizations. In making successful policies and protocols, the participation of the government is instrumental to effectively monitoring the applicability of the policy. The CE adoption relates to environmental protection; thus government shall promote it and further monitor its implementation in industries, such as TAI, automotive, agricultural, etc. (Dohale, Ambilkar, Kumar, Mangla, et al. 2023). The findings of the present study are endorsed by Govindan et al., (2016), who claimed that weaker governmental involvement and practices in policy formation lead to inappropriate awareness about green practices. Thus, the analysis of this research work recommends creating circular economy awareness and protocols to solve challenges related to the barriers - unawareness of adoption policies (B8) and unawareness about CE-ST adoption (B1). It is essential to demonstrate the policies and benefits associated with CE-ST adoption to create awareness among all stakeholders of TAI to gain the additive advantages of CE-ST implementation. Majumdar et al. (2021a) have highlighted the benefits to TAI through industry 4.0 technology adoption. Whereas Majumdar and Sinha (2019) discussed the various advantages of adopting sustainable CE practices in TAI. Further, the well-communicated benefits result in increased awareness about the policy implementation (Kumar et al. 2021). Thus, once the benefits of CE-ST implementation are understood, the awareness about its implementation will be increased in TAI. Further, increased awareness amongst the practitioners results in minimizing the resistance to cultural change (B11) through implementing CE-ST in TAI.

Successful policy implementation largely depends on the availability of a trained workforce (Majumdar, Garg, et al. 2021). Further, the minimization of resistance to cultural change due to CE-ST adoption results in gaining the interest of the workforce by making a behavioral change to actively participate in the training programs. ILO (2019) reported that around 163 industries from 44 countries were unable to implement CE and ST of Industry 4.0 due to the unavailability of skilled resources (B3), i.e. workers. The government of India has started many initiatives, such as – ‘Skill India’, ‘Digital India’, ‘Make in India’, ‘National Policy for Advanced Manufacturing’, ‘Swachh Bharat’, etc., to improve the skill set of the workforce, and enhance the country’s infrastructure for CE and ST adoption. This development can aid in resolving the problems related to the - lack of circular SC design aspects (B10), lack of digital infrastructure (B4), unavailability of generic framework (B2), and lack of capability and motivation (B5). According to an estimation, the CE adoption in India leads to creating more than 8 million job opportunities (Kumar et al. 2021) which aids in overcoming the lack of acceptability (B9) barrier. The ever-changing digital and circular environment, policies formulated by the government, and the improvement in the skillsets, will aid the TAI practitioners in realizing the benefits of CE-ST and may motivate to implement CE-ST in their organizations.

6 Recommendations and Implications

6.1 Policy Recommendations

The present research work was developed to facilitate the stakeholders and practitioners working within the textile and apparel industries to understand the potential barriers to CE-ST implementation and formulate strategies for mitigation. The Neutrosophic ISM model (digraph) developed in this research can be beneficial for TAI practitioners to develop suitable plans for the successful CE-ST implementation based on the influence level of barriers. TAI practitioners can emphasize on bottom-level barriers having the highest driving force, i.e. lack of government support and subsidies (B6), unawareness about CE-ST adoption (B1), lack of digital infrastructure (B4), and resistance to cultural change (B11). Government authorities and the company stakeholders shall collaborate to formulate policies to motivate the CE-ST implementation in the textile and apparel industries.

The collaborative efforts can facilitate a cultural transformation of the organization to create awareness. Unawareness of adoption policies (B8) and Unawareness about CE-ST adoption (B1) are complementary to each other, and thus, an effective organizational awareness can result in mitigating these barriers. The awareness about B8 and B1 can be determined by performing surveys in industries. The government shall promote different rewarding benefits to organizations adopting the CE-ST. The government should ensure the financial support and subsidies to build CE-ST enabled facilities to produce eco-friendly products by implementing the sustainability concept. Organizations, along with a survey on determining awareness, shall also investigate the behavioral response of workers to cultural change. The resistance to cultural change can largely impact the organizations' operations while implementing CE-ST.

Top management shall develop strategies for the intermediate barriers, such as - unavailability of skilled resources (B3), unavailability of generic framework (B2), lack of digital infrastructure (B4), and lack of circular SC design aspects (B10). Suitable training programs conducted by government or private organizations shall be considered for enriching the skills of workers to strengthen workers for implementing CE-ST in organizations. These programs will also help workers understand the different frameworks and circular SC structures and select suitable ones. Despite lack of acceptability (B9), lack of knowledge about CE practices (B7), and lack of capability and motivation (B5), are the least influential barriers, these are equally crucial in the long-term view of CE-ST implementations. Motivation from the top management can help to overcome these barriers. The proposed recommendations and implications of the present research work are in line with Majumdar and Sinha (2019) and Majumdar et al. (2021a). Following the recommendations and adopting the proposed strategies provided in the present research work, the textile and apparel industries are expected to utilize the benefits of CE-ST implementation.

6.2 Novel Implications from the Present Research

The proposed research has several implications for theory and practice.

- The present research work is an earlier attempt to analyze the effect of barriers to combined CE-ST implementation in the textile and apparel industries. The present research work identified the critical barriers that restrict the effective adoption of CE-ST within the Indian textile and apparel industries. This research, using a novel Neutrosophic ISM, developed a hierarchical model of the barriers, i.e. digraph, which can provide insights into the most influential barriers in CE-ST adoption in TAI.
- This study has identified the key strategies and tactics (explained in the discussion section) that help organizations overcome the identified critical barriers, namely – lack of government support and subsidies, unawareness about CE-ST adoption, and unawareness of adoption policies to ensure the streamlined implementation of CE-ST within TAI in India.
- The recommendations are provided for the practitioners, professionals, stakeholders, policymakers, top management working in TAI companies, and the government authorities to formulate effective policies for the organizations willing to adopt CE-ST to help during the transformation process.
- The application of Neutrosophic ISM in this research introduces a powerful tool for decision-makers within the Indian textile and apparel industries. By identifying and prioritizing the critical barriers hindering CE-ST adoption, organizations can make informed decisions on resource allocation, investment, and strategy formulation. The Neutrosophic ISM's ability to analyze complex relationships and dependencies among barriers provides a comprehensive understanding of the factors influencing CE-ST implementation. This empowers managers and policymakers to devise targeted interventions and allocate resources more effectively, thereby accelerating the transition towards sustainable practices in the industry.

- The significant implication of the present research to the theory is developing a novel form of ISM, i.e. Neutrosophic ISM. The present study has successfully demonstrated the application of the novel neutrosophic ISM in the actual problem. The neutrosophic ISM is utilized to determine the interrelationships amongst the barriers and compute the driving and dependence power to determine the criticality of barriers. The combination of neutrosophic theory with ISM aids in overcoming the disadvantages associated with other ISM types (as discussed in Table 2). Thus, the novel Neutrosophic ISM is a noteworthy addition and implication in the operations research domain.

These implications further emphasize the multifaceted contributions of the research, ranging from practical insights for industry practitioners to theoretical advancements within the academic realm. The research's holistic approach, combining theory and application through Neutrosophic ISM, not only addresses current barriers in CE-ST adoption but also paves the way for more robust decision-making frameworks and methodologies in the pursuit of sustainable development.

7 Conclusion, Limitations and Future Research

The world is witnessing a growing awareness from consumers about the sustainability and environmental issues that are triggering the textile and apparel industry (TAI) practitioners to rethink their operations through sustainable and smart perspectives to adopt circular economy practices and smart technologies. The innovative alliance of CE and smart technologies is conceptualized to adopt sustainability concepts in practice. However, the transformation and renovations of the organizational activities are the major hurdles. The present research work is conducted to identify the critical barriers intervening the adoption problem. This study identified and verified 11 critical barriers through a comprehensive review of existing literature and the validatory survey technique. This study developed a novel Neutrosophic ISM technique by integrating neutrosophic theory with the ISM method to determine the interrelationship and ‘driving and dependence power’ of barriers. Further, a digraph is created in which the barriers are structured at different levels based on their influence. The identified 11 barriers are clustered in four categories (autonomous, dependent, linking, and independent) using the driving and dependence power of barriers through MICMAC analysis.

Lack of knowledge about circular economy practices (B7), lack of acceptability (B9), and lack of circular SC design aspects (B10) are found to be dependent barriers having the highest dependency and least driving power. In this study, the barriers - unavailability of generic framework (B2), unavailability of skilled resources (human, financial, technical, etc.) (B3), Lack of digital infrastructure (B4), and Resistance for cultural change (B11) are identified as autonomous barriers. Only two barriers are identified as linkage barriers, implying the stability of the Neutrosophic ISM model. The identified linkage barriers are - unawareness about CSC and smart technology adoption (B1) and lack of capability and motivation (B5). Whereas the identified independent barriers, namely - lack of government support and subsidies (B6) and unawareness of adoption policies (B8), are the most influential barriers to adopting CE-ST and strongly impact the other barriers. It is crucial and strategically essential to mitigate these driving barriers to adopt CE-ST in TAI successfully. Further, the results and recommendations of this research work provide valuable insights for practitioners, stakeholders, and policymakers to develop strategies to ensure the awareness and adoptability of CE-ST.

This study has certain limitations which can be pursued in future studies. This work pertains to the textile and apparel sector. This study presented the adoption barriers of CE-ST in the Indian textile and apparel industry context. Every manufacturing industry has its own typology. Thus, the generalization of the results obtained from this work is limited to the textile and apparel industry. Thus, future research can identify the novel challenges to CE-ST adoption in different sectors such as – automotive, agricultural, healthcare, construction, food, electrical & electronics, etc. The textile and apparel industry can vary based on the country. Thus, similar studies can be performed in the textile and clothing industry of other developed and developing economies. It would be interesting to determine the changes in the patterns of these barriers concerning different localities through a comparative assessment. The novel Neutrosophic ISM is a flexible approach. It can be generalized to analyze the barriers, factors, risks, and enablers of implementing other aspects, viz. lean implementation, industry 4.0 implementation, blockchain adoption, etc., in the different domains.

The future work shall conduct case study base research by utilizing the MCDM approach, optimization tools, or machine learning based algorithms to gain a deeper understanding about the behavior of barriers in real-life cases. The current pandemic of COVID-19 has created awareness regarding resiliency in supply chains (Dohale, Verma, Gunasekaran, and Ambilkar 2023). This reduces the firms' focus on sustainability aspects (Chowdhury et al. 2021). Thus, future studies shall focus on creating a robust framework that can effectively create resilient and sustainable supply chains in different sectors utilizing smart technologies during post-COVID-19 situations.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Data Availability Statement

The author confirms that all data generated or analyzed during this study are included in this article [and its supplementary information files].

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Appendix A1. Identified Barriers to CE-ST adoption in TAI

Sr. No.	**Barriers**	**Description**	**References**
1	Unawareness about CE and ST adoption (B1)	Lack of understanding about the circular economy and smart technology results in unawareness of the benefits associated with the CE-ST adoption in TAI.	(Ghadimi et al. 2019; Kumar et al. 2021; Majumdar, Garg, et al. 2021; Majumdar and Sinha 2019; G. Yadav et al. 2020)
2	Problem of coordination and collaboration	The coordination and collaboration amongst members maintain transparency. Coordination and collaboration help to manage information sharing. More effective the coordination between supply chain members, more will be the development of smart information and communication system	(Luthra and Mangla 2018; G. Yadav et al. 2020; V. S. Yadav et al. 2020)
3	Unavailability of generic framework (B2)	TAI practitioners are witnessing difficulties in determining the effective procedure to implement CE-ST in their organizations due to unavailability of a globally accepted and well-validated framework.	(Batista et al. 2018; Chiappetta Jabbour et al. 2017; Kumar et al. 2021; Long et al. 2016; G. Yadav et al. 2020)
4	Unavailability of skilled resources (human, financial, technical, etc.) (B3)	There is a scarcity of resources with adequate technical skills and expertise to operate and run the smart technology-enabled systems and adopt CE strategies to implement in practice.	(Batista et al. 2018; Ghadimi et al. 2019; Kumar et al. 2021; Majumdar, Garg, et al. 2021; G. Yadav et al. 2020)
5	Lack of digital infrastructure (B4)	Lack of digital infrastructure to connect physical and virtual world. The existing infrastructure is insufficient to adopt smart technologies, which are facilitating CE practices	(Kamble et al. 2018; Kumar et al. 2021; Majumdar, Garg, et al. 2021; Majumdar and Sinha 2019)
6	Lack of capability and motivation (B5)	Improper capability to deploy smart technologies and CE strategies in the existing firms. Lack of motivation to understand sustainability aspect due to unavailability of incentive for adopting CE-ST	(Kumar et al. 2021; Luthra and Mangla 2018; G. Yadav et al. 2020)
7	Lack of government support and subsidies (B6)	Lack of financial support from the government in the form of incentives, subsidies. Lack of training programs related to CE-ST adoption by the government.	(Govindan et al. 2016; Kumar et al. 2021; Majumdar, Garg, et al. 2021; Muthu 2019; G. Yadav et al. 2020)
8	Lack of knowledge about CE practices (B7)	There is an unclear idea about the CE concept and the lack of CE practices implemented in TAI using smart technologies.	(Majumdar, Garg, et al. 2021; Majumdar and Sinha 2019; G. Yadav et al. 2020)
9	Company's poor digital operations vision and strategy	The adoption of smart technology and CE is long-term and can provide ROI after few years. However, the lack of long-term vision restricts firms to invest in ST and CE	(Luthra and Mangla 2018)

Sr. No.	Barriers	Description	References
10	Time constraint	The CE and ST implementation can require months of period. Whereas any technology-oriented problem can delay the process of implementation further. This makes lack of interest of practitioners to think CE-ST as suitable for TA	(Majumdar, Garg, et al. 2021; Rajput and Singh 2019a)
11	Unawareness of adoption policies (B8)	Lack of understandings about the strategies to cost-effectively implement the CE and smart technologies in TAI. Thus, restricting the stakeholders to invest in the implementation of CE-ST	(Ghadimi et al. 2019; Kirchherr et al. 2018; Kumar et al. 2021; Majumdar and Sinha 2019)
12	Lack of acceptability (B9)	The benefits of CE-ST are documented well. However, no real example to demonstrate the return on investment and security concerns of adopting CE-ST. This reduces the acceptance rate.	(Luthra and Mangla 2018; Majumdar, Sinha, et al. 2021; G. Yadav et al. 2020)
13	Lack of circular SC design aspects (B10)	Lack of understanding about the circular SC aspects of the product comprising recycling, redesigning, remanufacturing, refurbishing, regeneration, and restoration to develop CE business models due to inefficient smart technology digitalization	(Kumar et al. 2021; Lahane et al. 2020; Rajput and Singh 2019b; G. Yadav et al. 2020)
14	Complexity within supply chain configuration	Extremely complex SC configurations of CE and digital technologies. This results in a lack of interest from TAI experts to implement CE-ST	(G. Yadav et al. 2020)
15	Resistance for cultural change (B11)	Workers in TAI are always under fear of witnessing cultural change. Workers are always in the mindset that smart technologies take away their jobs. Being financially unstable, digitization and the environment is not on their priority list. They resist technology adoption. While, for CE adoption, a change in organizational culture is needed. Employees resist to the culture change, which makes CE adoption difficult	(Kirchherr et al. 2018; Kumar et al. 2021; Liboni et al. 2018; Majumdar, Sinha, et al. 2021; Mangla et al. 2019; G. Yadav et al. 2020)

Appendix A2. Profile of respondents participated in validatory survey

Particulars	**Content**	**No. of Experts**	**%**
Academic Qualification	Ph.D.	26	26.53%
	Post-Graduate	53	54.08%
	Graduate	19	19.39%
Designation	Director	3	3.06%
	Top Level Manager	42	42.86%
	Senior Level managers	26	26.53%
	Junior Level Managers	11	11.22%
	Academicians	16	16.33%
Work Experience	Above 25 Years	17	17.35%
	21-25 Years	22	22.45%
	16-20 Years	47	47.96%
	11-15 Years	11	11.22%
	10 Years	1	1.02%

Appendix A3. Profile of the experts contacted for Neutrosophic ISM

Expert	Background	Designation	Educational Qualification	Experience (No. of Years)
Expert-1	Industry	Director, Production	Ph.D.	23+
Expert-2	Industry	Senior IT Manager	Post-graduate	14+
Expert-3	Industry	Sustainable Operation Manager	Ph.D.	19+
Expert-4	Industry	Senior Sustainable Production Manager	Post-Graduate	12+
Expert-5	Industry	Chief Technical Officer	Post-Graduate	22+
Expert-6	Industry	Senior IT Manager	Post-Graduate	18+
Expert-7	Industry	Senior Manager - Environment Management	Post-Graduate	17+
Expert-8	Industry	Manager – Circular Supply Chain	Ph.D.	15+