Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Analyzing Industry 4.0 Integration Challenges in Sust ainable Supply Chains: A Study of Bangladesh's RMG Industry Using Fuzzy AHP and BWM

Monowar Wadud Hridoy
Chittagong University of Engineering and Technology
Sayef Ahmed
sayefsowro@gmail.com

Ahsanullah University of Science and Technology

Article

Keywords: Industry 4.0, Sustainable Supply Chain Management, RMG Industry, Fuzzy AHP, Best-Worst Method

Posted Date: November 19th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11430272/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Analyzing Industry 4.0 Integration Challenges in Sustainable Supply Chains: A Study of Bangladesh's RMG Industry Using Fuzzy AHP and BWM

Monowar Wadud Hridoy[1] and Sayef Ahmed[2*]

[1]Department of Mechatronics and Industrial Engineering, Chittagong University of Engineering and Technology, Chattogram-4349, Bangladesh

[2]Department of Textile Engineering, Ahsanullah University of Science and Technology, Bangladesh

***Corresponding Author:** Sayef Ahmed, Email: sayefsowro@gmail.com*

Abstract:

This study examines the challenges of integrating Industry 4.0 technologies into supply chain management to promote sustainable development in Bangladesh's ready-made garment sector. Although Industry 4.0 offers significant potential, its adoption is hindered by multiple interconnected barriers. Through literature review and expert consultation, fifteen key obstacles were identified and prioritized using Fuzzy AHP and the Best-Worst Method. The results consistently highlight leadership and policy-related constraints as the most critical challenges. The study emphasizes the importance of strong institutional support and strategic direction, and proposes a practical roadmap to support digital transformation in labor-intensive industries within emerging economies.

Keywords: Industry 4.0, Sustainable Supply Chain Management, RMG Industry, Fuzzy AHP, Best-Worst Method

1. Introduction

Despite being a cornerstone of the economy of Bangladesh, the Ready-Made Garment (RMG) sector is besieged by a confluence of systemic vulnerabilities that threaten its global competitiveness and long-term viability. Recent catastrophic incidents like the Rana Plaza collapse and a litany of factory fire incidents have exacted a devastating human toll (Bair et al., 2020; Barua & Ansary, 2017; N. Hossain, 2019; S. Islam et al., 2022; Miller, 2012; Sumon et al., 2017). These pre-existing challenges were dramatically intensified by the COVID-19 pandemic. Widespread order cancellations and deferrals from international retailers during global lockdowns led to severe operational disruptions and unprecedented financial losses, costing the sector billions in revenue. (T. Islam & Halim, 2022; Kabir et al., 2021; Majumdar et al., 2020; Rahaman & Islam, 2021). Furthermore, the sector is crippled by the presence of opportunistic domestic syndicates, causing a substantial lead time disadvantage compared to regional competitors (M. Chowdhury et al., 2014). These challenges underscore the urgent need for sustainable supply chain practices that harmonize economic growth with environmental stewardship and social equity. Without systemic transformation, the industry risks losing its competitive edge in an increasingly eco-conscious global market.

The RMG sector of Bangladesh serves as the linchpin of national economy, contributing over 11% to GDP and employing more than 4 million workers, approximately 80% of whom are women. Positioned as the world's second-largest apparel exporter, the sector holds a 6.5% share of global RMG trade. It is the primary source of foreign exchange, accounting for 84% of the nation's total exports and generating over 35 billion local currencies in annual earnings (R. S. Chowdhury et al., 2022). In the fiscal year of 2019-20, the earnings have risen to 27949.19 million USD which was 32.57 million USD in the fiscal year 1983-84 (Bhattacharya et al., 2002). This dramatic increase shows how the sector has grown, catalyzing urbanization, poverty reduction, and female empowerment. This huge sector now stands at a critical juncture confronted by global

competition (Hossian et al., 2019), shifting consumer demands for sustainability (Matemilola et al., 2020) and persistent internal inefficiencies that threaten its market position (C. L. & M., 2016). International buyers now demand lead times of 35-40 days. This presents a significant hurdle for Bangladesh, where the current lead time stands at 90-120 days. It is considerably longer than those of competing nations like Sri Lanka (19-45 days), Vietnam (60 days), China (40-50 days), and India (50-70 days) (Rahman & Anwar, 2006). While India and China benefit from domestic raw material sources, and Vietnam and Cambodia enjoy expedited logistics due to their close proximity to Chinese manufacturing hubs, the geographical positioning of Bangladesh confer no such advantage (Haque, 2009; Samad et al., 2023). Contemporary research in the RMG sector have identified supply chain disruption risk and highlighted persistent issues like production and shipment delays caused by raw material availability and price instability (Bala et al., 2020; N. A. Chowdhury et al., 2019). The sector's vulnerability after the COVID-19 pandemic has attracted researchers to model the crisis, identify negative impacts and evaluate strategic countermeasures (Taqi et al., 2020). Case-study on the challenges of Corporate Social Responsibility (CSR) have concluded that the prevailing profit-maximization mindset among suppliers, coupled with corruption and insufficient regulatory frameworks are the primary barriers to meaningful CSR adoption (P. K. Saha et al., 2021). These challenges underscore the need for greater supply chain diversification and sustainable business models.

The global industrial landscape is undergoing a fundamental shift toward sustainability. Composting and anaerobic digestion are becoming key sustainable waste management solutions for the food industry (Rabbi & Amin, 2024). Firms are increasingly integrating sustainable green logistics with remanufacturing operations for achieving circular economy goals (Nikseresht et al., 2024). Green composites and Phase change materials have emerged as major frontiers in material manufacturing industries, primarily due to their crucial role in advancing sustainability goals (Chabba et al., 2005; M. I. Hossain et al., 2025). The electronics industry is actively investigating the ecosystem of repair-oriented design, focused on identifying key barriers and drivers that influence its implementation (Ipaki & Hosseini, 2025). To align with the broader industrial transition to sustainability, supply chain management must undergo a fundamental transformation. The integration of Industry 4.0 principles into supply chain management offers a viable framework for attaining sustainability while addressing persistent, multifaceted inefficiencies.

Industry 4.0 (I4.0) is characterized by cyber-physical systems where IoT, and AI-driven automation promises to revolutionize industrial landscape. The transformative power of IoT is redefining efficiency across a vast spectrum, from smart factories to adaptive infrastructures for smart cities (Balamurugan et al., 2022; Chamekh et al., 2018; M. M. Hasan et al., 2025; Li et al., 2017). AI-driven demand forecasting is playing a crucial role to minimize overproduction and inventory waste (Praveen Kumar et al., 2024; Sajja et al., 2025). By integrating smart technologies, I4.0 enables real-time data analytics, predictive maintenance, and decentralized decision-making. Thus, it reduces operational inefficiencies and waste (Bai et al., 2020). For the RMG sector, this translates into enhanced productivity, reduced lead times, and improved quality control. All of these are critical factors in a hyper-competitive market. The integration of I4.0 with Sustainable Supply Chain Management (SSCM) offers a transformative pathway for enhancing operational and environmental performance. Furthermore, blockchain technology provides authentication of sustainable practices, strengthening compliance with global standards (Horner & Ryan, 2019; Kshetri, 2021). Despite these potential benefits, Bangladesh's RMG sector lags in I4.0 adoption due to multifaceted barriers. Understanding these barriers is a critical imperative for ensuring the sustainable growth and global competitiveness of the industry. Bangladeshi manufacturers risk falling behind competitors in regions where digital transformation is already underway (Bag et al., 2023; Sharma et al., 2023; Zhang et al., 2023). Therefore, addressing these impediments is pivotal to unlocking I4.0's role as an enabler of sustainability.

Building upon a mixed-methods approach that combines a literature review with field surveys in RMG industries, this study identifies 15 critical impediments to I4.0-SSCM integration. These barriers are clustered into five dimensions to provide a granular and empirically-grounded understanding of the adoption challenges in the RMG sector. The study also proposes a policy roadmap to accelerate I4.0-driven

sustainable transformation. Throughout the study, the authors try to pursue the following research questions:

RQ1. What are the most critical barriers hindering Industry 4.0 adoption in sustainable supply chain management within Bangladesh's RMG sector?

RQ2. How can two MCDM approaches (Fuzzy AHP & BWM) enhance the robustness of barrier analysis compared to single-method frameworks?

RQ3. What strategic interventions should stakeholders prioritize to accelerate I4.0 adoption for sustainable RMG supply chains in emerging economies?

To address these questions, this study employs two MCDM techniques. Both Fuzzy Analytic Hierarchy Process (FAHP) and Best-Worst Method (BWM) were used to systematically evaluate and prioritize the challenges hindering Industry 4.0 adoption in the RMG sector. In general, AHP serves to capture the inherent uncertainty and subjectivity in expert judgments by converting linguistic evaluations into triangular fuzzy numbers. It provides a nuanced understanding of challenge priorities through fuzzy weight ranges (Yang & Chen, 2004). BWM compliments this by focusing on the most and least important criteria, yielding precise crisp weights through an optimization model that minimizes judgmental inconsistencies (Singh & Pant, 2021). That is why, both of these methods have been brought together in order to derive a multi-dimensional assessment. While FAHP delivers depth by quantifying ambiguity, BWM provides clarity in identifying non-negotiable priorities. The synergistic application of both techniques offers complementary lenses for understanding the complex ecosystem of Industry 4.0 adoption barriers.

The motivation of this study is threefold. Firstly, it motivates to safeguard the RMG sector's economic viability in an era of digital and green transitions. Secondly, the study is determined to equip policymakers and industry leaders with actionable insights for targeted interventions. Identifying the root impediments should allow stakeholders to allocate resources strategically. Finally, the authors wish to contribute a methodological blueprint for barrier analysis in comparable industrial contexts. The study's Fuzzy AHP and BWM approach offers a replicable framework for other emerging economies grappling with similar challenges. By prioritizing barriers through robust MCDM techniques, this research provides empirical grounding for policy and investment decisions.

The rest of the research paper is organized as follows: Section 2 outlines the relevant works and the contributions of this study in the existing literature. Section 3 discusses the methodology of applying the two MCDM techniques to prioritize the barriers. Section 4 analyzes how the challenges of I4.0 are ranked globally and demonstrates a practical roadmap upon implementation of I4.0 in RMG context. Finally, the study is recapitulated in Section 5, providing the policy recommendations and a strategic roadmap for implementation.

2. Literature review:

The pursuit of sustainability in supply chains has generated a diverse and complex body of literature, which can be categorized into studies on strategic implementation trade-offs, key enabling technologies, and critical adoption barriers. Lummus et al., (2001) defined Supply Chain Sustainability Management (SCSM) focusing on the linear management of activities from raw material to customer order to ensure operational efficiency. While this definition is process oriented, it lacks an explicit consideration of environmental or social dimensions. Stock & Boyer, (2009) provided an extended definition of SCSM from a network-based perspective, involving multiple interdependent organizations. Although this definition introduces a broader strategic objective beyond mere delivery, its focus remains on economic performance and customer satisfaction, with sustainability implied rather than stated. Seuring & Müller, (2008) provided the most comprehensive definition of SCSM, that integrates the management of material, information, and capital flows with the explicit goal of balancing all three pillars of sustainable development—economic, environmental, and social. This definition represents a holistic and modern understanding of SCSM.

A substantial body of literature positions I4.0 technology as a primary enabler for overcoming barriers of supply chain sustainability. Kamble et al., (2022) provided a comprehensive systematic review of digital twin technology within manufacturing supply chains. The study positioned digital twinning as a pivotal tool for enhancing sustainability. They demonstrated that integration of technologies such as IoT, cloud computing, and blockchain leads to significant advantages in predictive maintenance and overall productivity. Dalal et al., (2024) proposed a novel hybrid model integrating Convolutional Neural Networks (CNNs) and Bidirectional Long Short-Term Memory (BiLSTM) networks to improve demand forecasting and resource allocation. The authors reported 96.57% accuracy, suggesting a significant potential for such AI models to minimize waste and enhance operational efficiency, thereby contributing to environmental and economic sustainability goals simultaneously. Contemporary research by supply chain scholars globally has systematically expanded to address the integration of digital transformation for building resilient and sustainable operation. Empirical studies demonstrate this trend across various contexts. Bag et al., (2023) examined the application of I4.0 tools for achieving sustainability in the supply chain operations of South African manufacturing firms. Using variance-based Partial Least Squares Structural Equation Modelling (PLS-SEM), their research confirmed that the use of I4.0 tools directly led to improved resource consumption and reduced waste. Sharma et al., (2023) investigated the practical application of digital technology to create sustainable fruit supply chains in Uttarakhand, India. Their research highlighted the potential of digital ecosystems to improve incomes and efficiency for smallholder farmers. Said et al., (2025) assessed the potential for a sustainable bioenergy supply chain derived from biomass waste in Egypt. Their application of digital technology on energy recovery transformed a critical waste management problem into a cornerstone of a national sustainable energy strategy. Shekoohi Tolgari & Zarrinpoor, (2024) addressed the complex challenge of designing a SSCM system for the pharmaceutical industry by developing a mathematical optimization model that simultaneously pursues economic, social, and environmental objectives while accounting for the critical factors of product perishability and parameter uncertainty. Focusing specifically on decarbonizing freight transportation, which is the largest source of carbon emissions, Dong & Li, (2025) used well-designed incentives in supply chain contracts as practical tools improving the alignment of economic and environmental sustainability. By developing novel contracting models, the authors demonstrate how contractual terms can motivate partners to shift towards greener transport modes.

However, the literature confirms that the deployment of Industry 4.0 tools is insufficient without strategic alignment and collaborative governance to guarantee sustainable outcomes. Biswas et al., (2023) introduced a critical strategic trade-off between traceability and sustainability in blockchain adoption using a game theory model. They presented a counter-intuitive finding that consumer distrust can actually deter blockchain implementation and transparency does not automatically equate to sustainability. McGrath et al., (2021) argued that meaningful sustainability outcomes depend more on building collaboration than a controlled approach centered on data gathering and monitoring. Nayal et al., (2023) identified strong management support, high supply chain integration, and favorable regulations as critical antecedents for blockchain adoption, based on Structural Equation Modeling (SEM) analysis of 316 Indian agriculture supply chain professionals. Therefore, it is imperative to first understand and address the specific barriers that impede the I4.0 synergy with sustainable supply chain management principles.

Multi-Criteria Decision-Making (MCDM) techniques demonstrate a critical role in identifying and prioritizing these impediments to sustainable practice. Kayikci et al., (2022) investigated the drivers for establishing a smart sustainable circular supply chain (SSCSC) in low and middle-income countries (LMICs) through a systematic review and the application of MCDM techniques. They applied BWM and TOPSIS to identify and prioritize drivers and their analysis reveals that economic sustainability is the most critical driver, underscoring the foundational role of financial viability. They also highlight that robust governance and institutional frameworks are prerequisites for effective sustainability initiatives in LMICs. Alshbili et al., (2021) conducted an investigation on the Libyan oil and gas sector through a qualitative study based on semi-structured interviews. Their research techniques identified critical institutional voids such as the absence of clear legal requirements, a lack of resources for regulatory bodies, and ineffective

civil society organizations as the primary impediments to sustainable practices. Sazvar et al., (2021) addresses the complex challenge of designing a supply chain that is both sustainable and resilient, particularly under conditions of uncertainty by using a fuzzy optimization approach. Their model is validated through a real-world case study of an influenza vaccine supply chain. Bai et al., (2022) applied the BWM to analyze the enablers for blockchain technology to improve sustainable supply chain transparency (SSCT). Zhang et al., (2023) investigate the drivers for implementing smart waste management in China by employing a mixed-methods approach and the fuzzy DEMATEL technique. The study identifies eleven key drivers and highlights the interconnected nature of technological, economic, and leadership enablers in advancing sustainability in the context of circular economy goals. Raj et al., (2020) investigated the barriers to I4.0 adoption in a cross-national context for manufacturing industries. They applied the Grey-DEMATEL method and identified 15 key barriers, pinpointing the absence of a clear digital strategy and resource scarcity as the most significant impediments. **Table 1** summarizes global research by supply chain scholars on introducing sustainability.

Table 1. Global Approaches to Enhancing Supply Chain Sustainability

Study & Reference	Regional Context	Tools	Key Contribution/ Findings
(Kamble et al., 2022)	Global model application	Digital Twin	Digital twins integrate systems for predictive maintenance and productivity gains, thereby enhancing sustainability.
(Dalal et al., 2024)	Global model application	CNN-BiLSTM Hybrid Model	AI-driven demand forecasting (96.57% accuracy) optimizes resource allocation, reducing waste and improving efficiency.
(Bag et al., 2023)	South Africa	PLS-SEM Analysis	Empirical evidence confirms I4.0 tool usage directly improves resource consumption and reduces waste in manufacturing.
(Alshbili et al., 2021)	Libyan Oil & Gas Sector	Qualitative Interviews	Institutional Voids works as a primary impediment. Absence of legal requirements; Lack of regulatory resources are also crucial.
(Sharma et al., 2023)	Uttarakhand, India	Digital Ecosystems	Digital technologies improve supply chain efficiency and incomes for smallholder farmers in agricultural contexts.
(Zhang et al., 2023)	Chinese Supply Chains	Fuzzy DEMATEL	Technological price-performance; Management support; Operational challenges are crucial barriers.
(Said et al., 2025)	Egypt	Digital Tech for Bioenergy	Technology enables the transformation of biomass waste into a sustainable energy source, addressing waste management.
(Bai et al., 2022)	African Cocoa Supply Chain	Best-Worst Method (BWM)	Inherent technical characteristic of the technology itself works as the primary enabler.
(Raj et al., 2020)	Global model application	Grey-DEMATEL	Lack of a digital strategy and Resource scarcity are primary barriers to I4.0 adoption in manufacturing industries globally.
(Shekoohi Tolgari & Zarrinpoor, 2024)	Global model application	Mathematical Optimization	A robust optimization model balances economic, social, and environmental objective under uncertainty for pharmaceuticals.
(Dong & Li, 2025)	Model Application	Supply Chain Contract Design	Innovative contracts create economic incentives for partners to adopt greener transport modes.
(Kayikci et al., 2022)	Low & Middle-Income Countries	BWM, TOPSIS	Economic viability is the primary driver. Further, robust governance & institutional frameworks are also key factors.
(Sazvar et al., 2021)	Influenza Vaccine Supply Chain	Fuzzy Optimization	Understanding the trade-offs between sustainability and resilience objectives is the key factor.

A significant stream of research focuses on the transformative potential of the I4.0 for the Bangladeshi RMG sector. Applying Porter's Diamond Model, Rumi et al., (2021) posited that the RMG sector possesses inherent advantages across all framework components, which can be substantially amplified through

Industry 4.0 digitalization. Ahmed et al., (2018) empirically assessed the on-ground performance of Green Supply Chain Management (GSCM) practices in the textile industries of Gazipur. Habib et al., (2022) used SEM on a large sample of 403 Bangladeshi garment manufacturers focusing on GSCM. These survey-based studies revealed a mixed picture. While a significant number of factories are adopting various sustainable practices, the economic benefits are not uniformly realized. The researchers emphasized that cooperation with stakeholders and government policy in incentivizing green transitions is crucial for effective sustainable practices.

The literature within developing economies consistently reveals that the most profound impediments to sustainability are strategic and behavioral, rather than technical or financial. This is evidenced by sector-specific studies across key industries of Bangladesh. Moktadir et al., (2018) provide a critical analysis of the barriers to SSCM using grey-based DEMATEL approach within the Leather Industry. They identified that external market conditions and internal leadership deficits are fundamental drivers. Salman et al., (2024) integrated the Delphi technique with the DEMATEL method and revealed that I4.0 training, lack of motivation, and resistance to change are the most prominent barriers to I4.0 adoption within the RMG sector. M. Hossain et al., (2024) offers a hybrid approach of integrating BWM with Bayesian probability to identify barriers to Industrial Symbiosis (IS), a special case of sustainability, within the apparel sector. The most critical barrier they found is the lack of technology and infrastructure readiness. Aziz Khan et al., (2024) focused on medium-sized RMG enterprises in adopting sustainable practices. Utilizing the Fuzzy Delphi Method to effectively handle the ambiguity in expert judgments, the study identifies and prioritizes a distinct set of critical barriers, determining the financial viability as the foremost concern, with the higher prices of sustainable products and the high costs of sustainable technology being the most pressing obstacles. A. Kumar et al., (2020) utilized Fuzzy Analytical Hierarchy Process (FAHP) to find financial drivers, particularly the maximization of net return on investment, as the most powerful catalyst**. Table 2** provides a comparative summary of key studies investigating barriers to sustainable and digital supply chain adoption in Bangladeshi Industries. The table also highlights how the primary nature of the most critical barriers, whether financial, strategic or social, varies upon the specific industrial context.

Table 2. Comparative analysis of barrier studies in SSCM within Bangladeshi context

Reference	Industry	Context	Primary Methodology	Primary Barrier Type	Specific Top-Ranked Barriers
(Moktadir et al., 2018)	Leather	SSCM	Grey-DEMATEL	Strategic/Behavioral	Lack of customer awareness; Lack of top management commitment
(Salman et al., 2024)	RMG	I 4.0 Adoption	Delphi + DEMATEL	Socio-Technical	I4.0 Training; Lack of Motivation; Resistance to Change
(M. Hossain et al., 2024)	Apparel	Industrial Symbiosis	Bayesian BWM	Technological/Infrastructural	Lack of technology and infrastructure readiness
(Aziz Khan et al., 2024)	Medium-sized RMG	SSCM	Fuzzy Delphi	Financial/Economic	High price of sustainable products; High cost of technology
(A. Kumar et al., 2020)	RMG	SSCM	Fuzzy AHP	Financial/Economic	Maximization of net return on investment

2.1. Research gap and contribution

This study makes significant and novel contributions to both academic research and practical applications in the field of Industry 4.0 adoption for SSCM in the RMG sector of Bangladesh. Diverging from extant literature that often relies on single analytical techniques, this research introduces a robust methodological approach by applying both Fuzzy AHP and BWM techniques. By applying both methodologies, the study not only prioritizes the barriers but also cross-validates the findings, thereby producing a more reliable and

nuanced hierarchical structure. Moreover, this dual application process effectively addresses the inherent uncertainties in expert judgment-based decision making. Therefore, the study renders a substantial advancement over single-method approaches commonly found in existing literature. A critical and previously underemphasized insight emerging from this analysis is the primacy of institutional frameworks. Governmental policy gaps were identified as the most significant barrier, a finding that surpasses the financial and technological constraints often highlighted in prior research. This insight carries important implications for national industrial strategies and positions this study as uniquely valuable for policymakers. A key implication of this work is that, the study's framework can be relevant for other labor-intensive manufacturing sectors in emerging economies. The combination of methodological rigor and practical applicability sets a new standard for research in technology adoption and sustainable industrial development. The study concludes with actionable insights that can be directly implemented across multiple levels of RMG sector to drive meaningful Industry 4.0 adoption and sustainable transformation.

3. Methodology

3.1. Identification of the key barriers to successful I4.0 implementation

The study adopted a systematic approach to identify the most critical barriers hindering I4.0 adoption in the RMG sector of Bangladesh. Initially, a comprehensive list of potential barriers was compiled through an extensive review of existing literature on I4.0 implementation challenges in manufacturing and supply chain contexts. These barriers were then refined and validated through consultations with industry experts from RMG factories. Using a structured questionnaire, experts assessed the relevance and significance of each barrier and eliminated those that lacked consensus or were deemed redundant. This step ensured that the final list of barriers was both contextually relevant and aligned with the practical challenges faced by the RMG sector in Bangladesh. Through this process, 15 key barriers were identified and subsequently organized into five categories based on expert feedback. **Table 3** depicts the key barriers for successful implantation of I4.0 into supply chain management with a focus on achieving sustainability. Prior to the consultation, each expert received a participant information sheet explaining the purpose of the study, the voluntary nature of participation, the confidentiality of responses and the right to withdraw at any time, and informed consent was obtained from every expert before the structured questionnaire was administered (see Section 3.3).

Table 3. Barriers to industry 4.0 adoption in Bangladesh's RMG sector

Category	Barrier	Key Impact	Ref.
LPO: Leadership & Policy Obstacles	Lack of governmental support	Absence of clear policies/funding for I4.0 transition	(Calabrese et al., 2021; M. Hasan, 2017; M. A. Islam et al., 2018)
	Manager's approach	Resistance to tech-driven cultural/organizational changes	
	Lack of marketing tactics	Low awareness/practice of sustainable marketing	(Karmaker et al., 2023; Khondkar & Honey, 2022)
	Labor unrest	Strikes disrupt production and sustainable practices	
HRID: Human Resource & Infrastructure Gaps	Lack of training	Limits tech adoption and green supply chain practices	(Debnath et al., 2023; R. Kumar et al., 2020; Majumdar et al., 2021)
	Raw material accessibility	Import dependence increases costs/lead times	(Aziz et al., 2023; A. Y. Chowdhury et al., 2019)

	Workplace safety	Insufficient safety measures reduce worker satisfaction	(Hemphill & White, 2018; Sharmin, 2022)
TCH: Trade & Collaboration Hurdles	Custom clearance delays	Cross-border transaction inefficiencies	(K. B. Saha et al., n.d.)
	Poor coordination and collaborations	Weak collaboration hinders I4.0 implementation	(Cimini et al., 2020)
	Low I4.0 understanding	SMEs lack awareness of I4.0 benefits	(Bonekamp & Sure, 2015; Pereira & Romero, 2017)
OED: Operational & Environmental Risks	Load-unload inefficiencies	Long lead times from poor communication	(Moktadir et al., 2018; Rashid et al., 2024)
	Political instability	Policy uncertainty disrupts long-term planning	
	Unwilling behavior toward Industry 4.0	Unwillingness to adopt digital workflows	(Çiğdem et al., 2023; Haddud et al., 2017)
PESC: Production & Sustainability Issues	Worker inefficiency	Skills gap in ERP/Big Data/Cloud technologies	(M. Z. Hasan et al., 2020; Stentoft et al., 2021)
	Poor data quality	Limits smart factory implementation	

3.2. Data collection technique

To ensure the reliability and depth of insights, data were collected from highly experienced professionals within the RMG manufacturing sector. The survey was directed at professionals with at least three years of direct experience in the RMG manufacturing sector; the 20 respondents summarised in Table 4 had between 3 and 10 years of experience (mean 6.2 years), and 17 of them had five years or more. It was made sure that, the experts hold positions that provide them with substantial operational and strategic insights into Industry 4.0 challenges. Initial outreach was made to 26 companies across key RMG industrial hubs such as Dhaka, Gazipur, and Narayanganj regions, where the nation's largest garment manufacturers are concentrated. Industry selection criteria considered operational scale, geographical distribution, and research feasibility factors including cost, time, and resource constraints. Contact was established through multiple channels including email and mobile communications, followed by in-person visits to facilities when necessary. From this targeted approach, we received 20 complete responses from industry participants. The responses were subjected to a stringent screening process by an expert panel consisting of 8 experts. They excluded responses showing duplication, logical inconsistencies, or limited relevance to the subject context. This resulted in a final dataset of 8 high-quality responses from qualified decision-makers. **Table 4** shows the summary of survey respondents.

Table 4. Summary of survey respondents

SL No	Timestamp	Sector	Company Fixed Asset (Tk.)	Suppliers	ISO certification	Respondent Experience	Respondent expertise	Automation Level (Full/Semi)
1	30-08-23 11:09	Private	150M–500M	51–100	Yes	6	Supply chain management	Full
2	06-10-23 19:20	Public	150M–500M	101–200	Yes	6	Supply chain management	Full
3	12-11-23 13:02	Private	150M–500M	>200	Yes	5	Production and Operation	Semi

4	09-12-23 22:17	Private	150M–500M	1–50	Yes	8	Supply chain management	Less than Semi
5	09-12-23 22:48	Private	>500M	51–100	Yes	6	Quality Control	Semi
6	09-12-23 22:50	Private	150M–500M	51–100	Yes	7	Maintenance Department	Semi
7	09-12-23 23:03	Private	7.5M–150M	1–50	Yes	5	Supply chain management	Less than Semi
8	10-12-23 9:22	Private	7.5M–150M	1–50	Yes	6	Maintenance Department	Semi
9	10-12-23 21:00	Private	150M–500M	101–200	Yes	4	Industrial Engineering	Less than Semi
10	11-12-23 22:10	Private	150M–500M	>200	Yes	6	Supply chain management	Semi
11	12-12-23 9:48	Private	150M–500M	101–200	Yes	3	Production and Operation	Less than Semi
12	12-12-23 15:35	Private	150M–500M	51–100	Yes	6	Supply chain management	Less than Semi
13	12-12-23 21:10	Private	≈100M	51–100	Yes	8	Supply chain management	Above Semi
14	13-12-23 20:06	Private	150M–500M	51–100	Yes	10	Manager-Supply chain	Less than Semi
15	13-12-23 20:47	Private	150M–500M	1–50	Yes	5	Supply chain management	Less than Semi
16	16-12-23 23:32	Private	150M–500M	1–50	Yes	6	Production and Operation	Less than Semi
17	17-12-23 8:01	Private	Not specified	101–200	No	4	Supply chain management	Semi
18	17-12-23 17:13	Private	150M–500M	51–100	Yes	7	Supply chain management	Less than Semi
19	20-12-23 22:01	Private	150M–500M	51–100	Yes	9	Manager-Maintenance	Less than Semi
20	21-12-23 20:41	Private	150M–500M	51–100	Yes	6	Supply chain management	Semi

To strengthen the methodological foundation of our study, we calculated the mean and standard deviation (SD) values from a 5-point Likert scale survey for all challenges. The values are presented in **Table 5**. This allows us to objectively assess the relative importance of each challenge across industry experts. The mean scores indicated general consensus on criticality and the SD values revealed the degree of agreement or divergence among respondents. Additionally, these statistics provided an empirical basis for validating the challenges identified through literature review. By systematically analyzing both central tendency (mean) and response variability (SD), a layer of statistical rigor was added to the challenge identification process.

Table 5. Descriptive statistics of challenges to Industry 4.0 initiatives for sustainability orientation in supply chain

Serial No.	Challenges to Industry 4.0 diffusion to achieve sustainability in the supply chain for RMG industry	Mean	Std. Deviation
1	Low understanding on Industry 4.0 implications	3.67	0.77
2	Unwilling behavior toward Industry 4.0	3.5	0.79
3	Safety Of workplace	3.11	0.96
4	Accessibility of raw material	3.17	0.86
5	Problem of coordination and collaborations	3.28	0.89
6	Inefficiency of the workers	3.28	0.96
7	Political instability	3.22	0.94
8	Lack of training	3.39	0.78
9	Load-unload time	3.06	0.8
10	Lack of governmental support and policies	3.06	0.87
11	Lack of marketing tactics	3.22	0.94
12	Custom clearance	3.17	0.86
13	Managers approach	3.28	0.83
14	Labor unrest	3	0.69
15	Poor existing data quality	3.11	0.76

Figure 1 and **Figure 2** provide the graphical representation of mean and SD values, respectively.

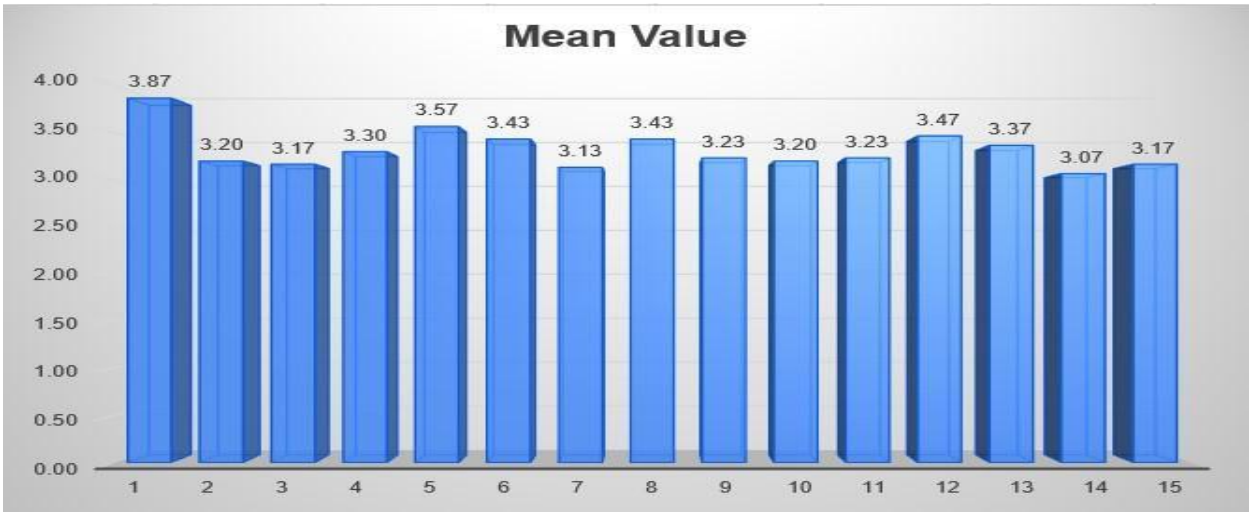


Figure 1. Mean value for the challenges

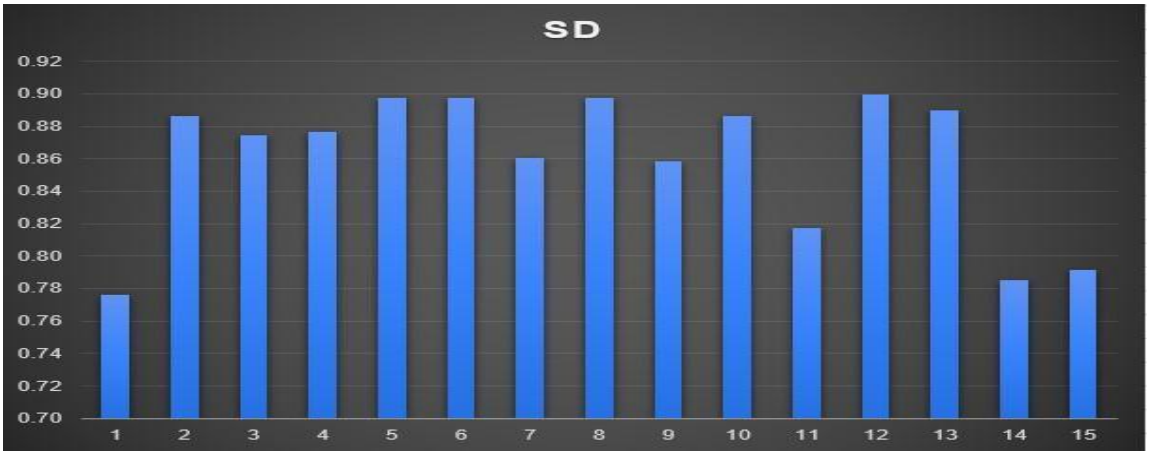


Figure 2. SD values for the challenges

While the sample size consisting of 8 experts may appear modest, it prioritizes depth of expertise over large quantities of data. The inputs from experts were gathered through a structured questionnaire designed to facilitate pairwise comparisons for both Fuzzy AHP (FAHP) and Best-Worst Method (BWM) analyses. FAHP is particularly valuable for its ability to handle the inherent uncertainty and subjectivity in expert judgments by converting linguistic evaluations into triangular fuzzy numbers. This approach not only captures the variability in expert opinions but also quantifies the degree of consensus or divergence among decision-makers. BWM offers a streamlined and efficient prioritization. This method enhances consistency in judgments and delivers crisp, interpretable weights that are easier to translate into actionable policy recommendations.

3.3. Ethical approval and informed consent

This study involved the collection of opinion data from adult industry professionals through structured questionnaires and expert consultations; no clinical procedures, interventions or biological samples were involved. All methods were carried out in accordance with relevant guidelines and regulations, including the Declaration of Helsinki and the research ethics guidelines. All experimental protocols, including the questionnaire, the participant information sheet and the informed-consent form, were approved.

Participation was entirely voluntary. Before data collection, every participant was informed in writing of the objectives of the study, the nature of the questions, the expected time commitment, the anonymous and confidential treatment of responses, the use of the data solely for academic research, and the right to withdraw at any time without giving a reason and without any consequence. Informed consent was obtained from all subjects before participation. This applies to all three stages of expert input used in this study: (i) the screening and validation of the barriers identified from the literature, (ii) the industry survey summarised in Table 4, and (iii) the pairwise comparisons provided for the Fuzzy AHP and Best-Worst Method analyses. All participants were adults (18 years or older) acting in their professional capacity; no minors or vulnerable individuals were involved, and consent from legal guardians was therefore not applicable. No personally identifiable information was retained in the analysis dataset, and all results are reported in aggregated form only. A blank copy of the participant information sheet and consent form is provided as Supplementary File S1.

3.4. Fuzzy Analytic Hierarchy Process (FAHP):

The Fuzzy Analytic Hierarchy Process (FAHP), proposed by Thomas L. Saaty is a sophisticated Multi-Criteria Decision Making (MCDM) technique. The process is useful for ranking, assessing and making decisions on complex multiple criteria. By disparting the decision problem into sub-sections that can each be interpreted separately and are more naturally understood, it reduces the risk of making wrong choice and

ensures the most appropriate decision (Saaty, 2013). The main advantage of AHP is that it is effective in handling multiple criteria to make decisions and it can cater to qualitative and quantitative data (Ho, 2008). It accepts the pair-wise comparison of each alternative that belongs to each criterion and offers a decision support tool for multicriteria decision-making problems. However, defective methodology of AHP can contaminate the findings and subsequent analyses and discussions (Cheng et al., 2002). Therefore, conventional AHP seems inadequate to capture the decision-maker's requirements explicitly. To model this kind of uncertainty in human preference, fuzzy sets could be incorporated with the pairwise comparison as an extension of AHP. Therefore, fuzzy AHP was proposed to equip classic AHP with the ability to accept uncertainty and ambiguity in human thinking style (Tan et al., 2014).

In this study, with a particular focus on supply chain sustainability, FAHP is used to assess challenges related to I4.0 implementation in RMG sector. Fuzzy numbers are used to describe expert preferences and fuzzy arithmetic is used to compute fuzzy ranking. FAHP is selected as it improves evaluation accuracy by adding fuzzy logic to account for uncertainty present in real-world scenarios. Evidence-based decision-making is facilitated by FAHP through pairwise comparisons and quantification of the criteria's relative value within a fuzzy framework.

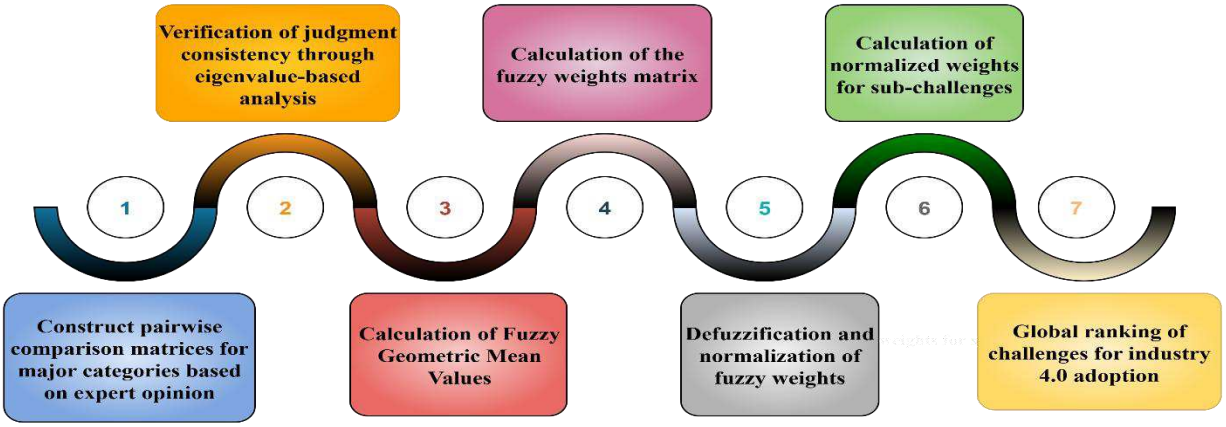


Figure 3. Roadmap of the Fuzzy AHP process

Figure 3 shows the framework for the fuzzy AHP process. The steps are described below in a sequential manner:

3.4.1. Construct pairwise comparison matrices for major categories based on expert opinion

The study commenced with the systematic development of fuzzy pairwise comparison matrices to evaluate the relative importance of the five major challenges. Expert judgments were collected using a linguistic scale shown in **Table 6,** that captures qualitative assessments of significance. Then, they were converted into triangular fuzzy numbers (TFNs) to account for inherent uncertainty in human decision-making. The table shows defined ranges for verbal expressions such as Moderate Significance or Absolute significance etc.

Table 6. Fuzzy triangular scale

Linguistic scale for significance	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Equal significance (ES)	(1, 1, 1)	(1,1,1)

Moderate significance (MS)	(2,3,4)	(1/4,1/3,1/2)
Strong significance (SS)	(4,5,6)	(1/6,1/5,1/4)
Very strong significance (VSS)	(6,7,8)	(1/8,1/7,1/6)
Absolute significance (AS)	(9,9,9)	(1/9,1/9,1/9)

Afterwards, through an aggregation of expert opinions, a fuzzy pairwise comparison matrix was constructed in **Table 7**. Here, each entry represented the fuzzy dominance of one criterion over another. For instance, LPO was judged to have "Very Strong Significance" over PESC (7.13,7.75,8.38), while HRID was deemed "Moderately Less Significant" than TCH (0.15,0.16,0.19). The diagonal elements were set to (1,1,1) to denote equal importance when comparing a criterion to itself, while off-diagonal entries reflected the fuzzy intensity of preference derived from expert consensus.

Table 7. Pairwise comparison matrix for five dimensions of challenges by aggregating the expert's opinion

Sl No	Major dimensions of challenges	LPO	HRID	TCH	OED	PESC
1	Leadership and Policy Obstacles (LPO)	1, 1, 1	3.25, 4.25, 5.25	1.5, 2.0, 2.5	3.25, 4.25, 5.25	7.13, 7.75, 8.38
2	Human Resource and Infrastructure Deficiencies (HRID)	0.20, 0.25, 0.34	1, 1, 1	0.15, 0.16, 0.19	0.24, 0.32, 0.47	3.75, 4.75, 5.75
3	Trade and Collaboration Hurdles (TCH)	0.63, 0.67, 0.75	4.75, 5.50, 6.50	1, 1, 1	2.13, 3.00, 3.88	6.38, 7.00, 8.13
4	Operational and Environmental Disruptions (OED)	0.20, 0.26, 0.36	2.25, 3.25, 4.25	0.33, 0.40, 0.53	1, 1, 1	3.25, 4.25, 5.25
5	Production Efficiency and Sustainability Concerns (PESC)	0.12, 0.13, 0.15	0.18, 0.23, 0.30	0.12, 0.14, 0.16	0.20, 0.25, 0.34	1,1,1

This step ensured a robust foundation for subsequent FAHP computations. The structured approach to matrix construction set the stage for rigorous consistency checks and weight derivation in later steps.

3.4.2. Verification of judgment consistency through eigenvalue-based analysis

To ensure logical coherence in the fuzzy pairwise comparison matrices, Saaty's eigenvalue method was adapted for fuzzy AHP consistency verification(Saaty, 1977). The consistency ratio (CR) was calculated mathematically. The consistency index (CI) was derived from **Equation 1**, where the principal eigenvalue (λ_{max}) was derived as the arithmetic mean of eigenvalues computed from the defuzzified comparison matrix and N represents the number of criteria or matrix order. In **Equation 2**, CR is defined as a ratio between the consistency of a given evaluation matrix and the consistency of a random matrix where RI is a random index. **Table 8** shows the universal values of RI, which depends on the matrix order (N) (Getawa Ayalew et al., 2024). All the numerical values that are essential for the calculation of CR are presented in **Table 9**. A CR value of less than or equal to 0.10 is acceptable for further proceeding with the investigation. If the CR value exceeds 0.10, the judgment must be re-examined from the inception in order to identify the cause of the discrepancy and make changes as needed(Saaty, 2013).

$$CI = \frac{\lambda_{max} - N}{N-1} \quad \text{.....1}$$

$$CR = \frac{CI}{RI} \quad \text{.....2}$$

Table 8. Random consistency Index (Getawa Ayalew et al., 2024)

N	3	4	5	6	7	8	9	10
RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 9. Consistency check for Major dimensions of challenges

	λ_{max}	N	CI	RI	CR
Major dimensions of challenges	5.33128	5	0.1041	1.12	0.0287<0.1

The obtained CR value of 0.0287 is substantially below the 0.1 threshold which confirms the acceptable transitivity in expert judgments. This mathematical validation ensured the fuzzy comparison matrices maintained necessary consistency before progressing to weight calculation. The eigenvalue-based approach, thereby upholds the methodological integrity of the FAHP implementation.

3.4.3. Calculation of Fuzzy Geometric Mean Values

After checking the validation of expert opinion, the relative importance of each major challenge dimension is computed from fuzzy geometric mean values using a systematic aggregation approach. For each criterion, the fuzzy comparison values provided by experts were combined using geometric mean operations from **Equation 3 & Equation 4.**

r_i = (A1⊕A2⊕A3⊕A4⊕A5)$^{\frac{1}{no\ of\ categories}}$ …… 3

A1*A2= (l1, m1, n1) * (l2, m2, n2) = (l1*l2, m1*m2, n1*n2) ……..…..…….. 4

Table 10 represents the geometric mean values of the major dimensions of the challenges.

Table 10. Geometric mean values of the major dimensions of the challenges

S. No	Major dimensions of challenges	LPO	HRID	TCH	OED	PESC	r_i
1	Leadership and Policy Obstacles (LPO)	1, 1, 1	3.25, 4.25, 5.25	1.5, 2.0, 2.5	3.25, 4.25, 5.25	7.13, 7.75, 8.38	2.573, 3.086, 3.566
2	Human Resource and Infrastructure Deficiencies (HRID)	0.20, 0.25, 0.34	1, 1, 1	0.15, 0.16, 0.19	0.24, 0.32, 0.47	3.75, 4.75, 5.75	0.481, 0.573, 0.708
3	Trade and Collaboration Hurdles (TCH)	0.63, 0.67, 0.75	4.75, 5.50, 6.5	1, 1, 1	2.13, 3.00, 3.88	6.38, 7.00, 8.13	2.093, 2.383, 2.736
4	Operational and Environmental Disruptions (OED)	0.20, 0.26, 0.36	2.25, 3.25, 4.25	0.33, 0.40, 0.53	1, 1, 1	3.25, 4.25, 5.25	0.868, 1.074, 1.34
5	Production Efficiency and Sustainability Concerns (PESC)	0.12, 0.13, 0.15	0.18, 0.23, 0.3	0.12, 0.14, 0.16	0.20, 0.25, 0.34	1, 1, 1	0.221, 0.254, 0.2997

The resulting fuzzy geometric mean (ri) for LPO (2.573, 3.086, 3.566) indicates its aggregated importance relative to other challenges. Similarly, this process yields fuzzy geometric means such as (0.481, 0.573, 0.708) for HRID and (2.093, 2.383, 2.736) for TCH. This step ensured that expert judgments were mathematically synthesized while preserving the uncertainty inherent in fuzzy assessments. The geometric mean method was chosen for its ability to minimize bias from extreme values and maintain the ratio properties essential for accurate weight derivation in FAHP.

3.4.4. Calculation of the fuzzy weight matrix

This step transforms the fuzzy geometric means (ri) into normalized fuzzy weights (wi). It represents the relative importance of each challenge dimension. The process involves two key operations. First, by **Equation 5**, the fuzzy geometric means (ri) of all criteria are added together using fuzzy addition rules. Next, in **Equation 6**, each criterion's fuzzy weight (w_i) is derived by multiplying its fuzzy geometric mean (ri) with the inverse of the total sum.

$$r1 \oplus r2 \oplus \cdots \oplus rn = (l1 + l2 + \cdots + ln, m1 + m2 + \cdots + mn, u1 + u2 + \cdots + un) \quad \ldots\ldots\ldots\ldots 5$$

$$w_i = r_i \otimes (r_1 \oplus r_2 \oplus \cdots \cdots \oplus r_n)^{-1} \quad \ldots\ldots\ldots\

Table 12 shows the defuzzified weights after calculation. This approach effectively captures the central tendency of the fuzzy weights while mitigating the influence of extreme values. For instance, the fuzzy weight of Leadership and Policy Obstacles was transformed into a crisp value of 0.42925, reinforcing its dominance among the challenge dimensions.

Table 12. Defuzzified and Normalized weight of Major dimensions of challenges.

Major dimensions of challenges	Defuzzified $\widetilde{w_i}$	Normalized wi_r	Ranking
LPO	0.42925	0.3411	1st
HRID	0.08232	0.0654	5th
TCH	0.33467	0.2659	2nd
OED	0.15367	0.1221	4th
PESC	0.25841	0.2053	3rd
TOTAL	1.25831	1	

The normalization process adjusted the defuzzified weights proportionally, yielding a coherent priority distribution where LPO (0.3411) retained its top rank. It is followed by Trade and Collaboration Hurdles (TCH = 0.2659) and Production Efficiency and Sustainability Concerns (PESC = 0.2053). Human Resource and Infrastructure Deficiencies (HRID = 0.0654) and Operational and Environmental Disruptions (OED = 0.1221) occupied the lower priority tiers. The normalized weights serve as the foundation for subsequent hierarchical aggregation and final challenge prioritization, facilitating strategic intervention planning.

3.4.6. Calculation of normalized weights for sub-challenges

The hierarchical nature of the FAHP methodology necessitates the computation of local weights for sub-challenges within each major dimension. It follows the same rigorous procedure applied to the primary criteria. For every challenge category, separate fuzzy pairwise comparison matrices were constructed based on expert evaluations, where each sub-criterion was assessed relative to others within its parent dimension using triangular fuzzy numbers. The geometric mean method was employed to synthesize these fuzzy judgments, followed by defuzzification via the Center of Area (COA) technique to obtain crisp local weights. After that, the normalized weights for sub-challenges were derived by ensuring their sum to unity within each category, preserving the proportional relationships established through expert judgments. **Table 13-17** delineates the normalized weights for five major challenge dimensions of LPO, HRID, TCH, OED, PESC respectively.

Table 13 Pairwise comparison matrix for LPO and its Normalized weights.

SL No	Challenges	LPO 1	LPO 2	LPO 3	LPO 4	Normalized wi_r
1	LPO 1 (Managers approach)	1, 1, 1	0.19, 0.24, 0.32	5.13, 6.13, 7.13	3,4,5	0.28017
2	LPO 2 (Lack of governmental support and policies)	3.75, 4.75, 5.75	1, 1, 1	5.25, 6.25, 7.25	2.50, 3.50, 4.5	0.49393
3	LPO 3 (Lack of marketing tactics)	0.14, 0.17, 0.2	0.14, 0.16, 0.2	1,1,1	0.72, 0.75, 0.81	0.09057

4	LPO 4 (Labor unrest)	0.21, 0.27, 0.38	0.23, 0.30, 0.44	1.38, 1.75, 2.13	1, 1 ,1	0.13534
Consistency Ratio= 0.0812						

Table 13 demonstrates that, within Leadership and Policy Obstacles (LPO), "Lack of governmental support (LPO2)" emerged as the most critical sub-challenge with a normalized weight of 0.49393, while "Lack of marketing tactics (LPO3)" was deemed least significant at 0.09057.

Table 14 Pairwise comparison matrix for HRID and its Normalized weights.

SL No	Challenges	HRID 1	HRID 2	HRID 3	Normalized wi_r
1	HRID 1 (Lack of training)	1, 1, 1	2, 3, 4	4, 5, 6	0.56029
2	HRID 2 (Accessibility of raw material)	1/4, 1/3, 1/2	1, 1, 1	2, 3, 4	0.29402
3	HRID 3 (Safety Of workplace)	1/6, 1/5, 1/4	1/4, 1/3, 1/2	1, 1, 1	0.14569
Consistency Ratio= 0.0079					

Similarly, as depicted in **Table 14,** within the major challenge dimension of Human Resource and Infrastructure Deficiencies (HRID), sub-challenge of "Lack of training (HRID1)" dominated with a weight of 0.56029, reflecting its pronounced impact relative to infrastructure-related issues.

Consistency ratios (CR) for all sub-matrices were verified to be below the 0.1 threshold. It ensures the logical coherence of expert judgments. This step not only provided granular insights into the relative

Table 15 Pairwise comparison matrix for TCH and its Normalized weights

SL No	Challenges	TCH 1	TCH 2	TCH 3	Normalized wi_r
1	TCH 1 (Custom clearance)	1, 1, 1	0.15, 0.17, 0.21	0.24, 0.32, 0.47	0.16519
2	TCH 2 (Problem of coordination and collaborations)	5.25, 6.25, 7.25	1, 1, 1	2.75, 3.75, 4.75	0.5457
3	TCH 3 (Low understanding on Industry 4.0 implications)	2.25, 3.25, 4.25	0.22, 0.28, 0.41	1, 1, 1	0.28911
Consistency Ratio= 0.0463					

significance of individual challenges but also maintained methodological consistency with the overarching FAHP framework. This method enables a comprehensive prioritization of barriers to Industry 4.0 adoption. The resultant normalized weights serve as critical inputs for the subsequent calculation of global priorities, aiding a transparent decision-support mechanism.

Table 16 Pairwise comparison matrix for OED and its Normalized weights

SL No	Challenges	OED 1	OED 2	OED 3	Normalized wi_r
1	OED 1 (Load-unload time)	1, 1, 1	0.21, 0.27, 0.38	0.15, 0.17, 0.21	0.15588
2	OED 2 (Political instability)	3, 4, 5	1, 1, 1	0.17, 0.21, 0.25	0.27496
3	OED 3 (Unwilling behavior toward Industry 4.0)	5, 6, 7	4.50, 5.25, 6.25	1, 1, 1	0.56916
Consistency Ratio=0.0079					

Table 17 Pairwise comparison matrix for PESC and its Normalized weights

SL No	Challenges	PESC 1	PESC 2	Normalized wi_r
1	PESC 1 (Inefficiency of the workers)	1,1,1	0.19,0.24,0.33	0.36028
2	PESC 2 (Poor existing data quality)	3.5,4.5,5.5	1,1,1	0.63972

Table 15 presents the pairwise comparison matrix for TCH (Technological Challenges) along with their normalized weights. Among the identified factors, TCH 2 (Problem of coordination and collaborations) has the highest weight (0.5457), indicating it is the most significant technological challenge. This is followed by TCH 3 (Low understanding of Industry 4.0 implications) with a weight of 0.28911, while TCH 1 (Custom clearance) has the lowest priority (0.16519). The consistency ratio (CR = 0.0463) confirms that the judgments are consistent and acceptable.

Table 16 shows the pairwise comparison matrix for OED (Operational and Economic Challenges). The results indicate that OED 3 (Unwilling behavior toward Industry 4.0) is the most critical factor with the highest normalized weight (0.56916). OED 2 (Political instability) ranks second (0.27496), whereas OED 1 (Load/unload time) has the least influence (0.15588). The consistency ratio (CR = 0.0079) is well below the acceptable threshold, ensuring reliable comparisons.

Table 17 illustrates the pairwise comparison matrix for PESC (People and Socio-Economic Challenges). The findings reveal that PESC 2 (Poor existing data quality) holds the highest importance with a weight of 0.63972, significantly outweighing PESC 1 (Inefficiency of the workers), which has a weight of 0.36028. This indicates that data-related issues are more critical than workforce inefficiency in this category.

3.4.7. Global ranking of challenges for industry 4.0 adoption

The final phase of the FAHP methodology involves synthesizing the hierarchical weight structures to establish a global prioritization of challenges. By multiplying the normalized weights of each main dimension with the corresponding local weights of their sub-challenges, the study derived global weights that reflect the absolute importance of each barrier within the overall decision framework. This multiplicative aggregation ensured that both the macro-level significance of major dimensions and the micro-level influence of specific sub-challenges were proportionally incorporated. **Table 18** shows the obtained global rankings for each sub-challenge after calculation. This table systematically establishes a hierarchical framework of the potential barriers in the adoption of Industry 4.0 in supply chains.

Table 18 Ranking of challenges to Industry 4.0 initiatives for sustainability orientation in supply Chains

Main Dimensions	Relative weights	Sub challenges	Relative weights	Relative rankings	Global weights	Global rankings
Leadership and Policy Obstacles (LPO)	0.3411	LPO 1	0.28017	2nd	0.0955	4th
		LPO 2	0.49393	1st	0.1684	1st
		LPO 3	0.09057	4th	0.0308	12th
		LPO 4	0.13534	3rd	0.0461	8th
Human Resource and Infrastructure Deficiencies (HRID)	0.0654	HRID 1	0.56029	1st	0.0366	10th
		HRID 2	0.29402	2nd	0.0192	13th
		HRID 3	0.14569	3rd	0.00952	15th
Trade and Collaboration Hurdles (TCH)	0.2659	TCH1	0.16519	3rd	0.0439	9th
		TCH 2	0.5457	1st	0.1451	2nd
		TCH 3	0.28911	2nd	0.0768	5th
Operational and Environmental Disruptions (OED)	0.1221	OED 1	0.15588	3rd	0.01747	14th
		OED 2	0.27496	2nd	0.03082	11th
		OED 3	0.56916	1st	0.0638	7th
Production Efficiency and Sustainability Concerns (PESC)	0.2053	PESC 1	0.36028	2nd	0.07396	6th
		PESC 2	0.63972	1st	0.13133	3rd

The results revealed a clear hierarchy of impediments to Industry 4.0 adoption. **Lack of governmental support and policies (LPO2)** emerged as the foremost challenge with a global weight of 0.1684. This result underscores the critical role of policy frameworks in enabling technological transition. It was closely followed by Problem of coordination and collaborations (TCH2) with a score of 0.1451 and Poor existing data quality (PESC2: 0.13133). These highlight the systemic inefficiencies in inter-organizational collaboration and data infrastructure. Mid-tier challenges included Managers' approach (LPO1) and Unwilling behavior toward Industry 4.0 (OED3). Both of these issues collectively emphasized human and cultural barriers. Conversely, Safety of workplace (HRID3: 0.00952) and Load-unload time (OED1: 0.01747) ranked lowest, suggesting their relatively marginal impact compared to strategic and governance-related hurdles.

Figure 4 shows the global weights of each challenge, derived from Fuzzy AHP method. This global ranking

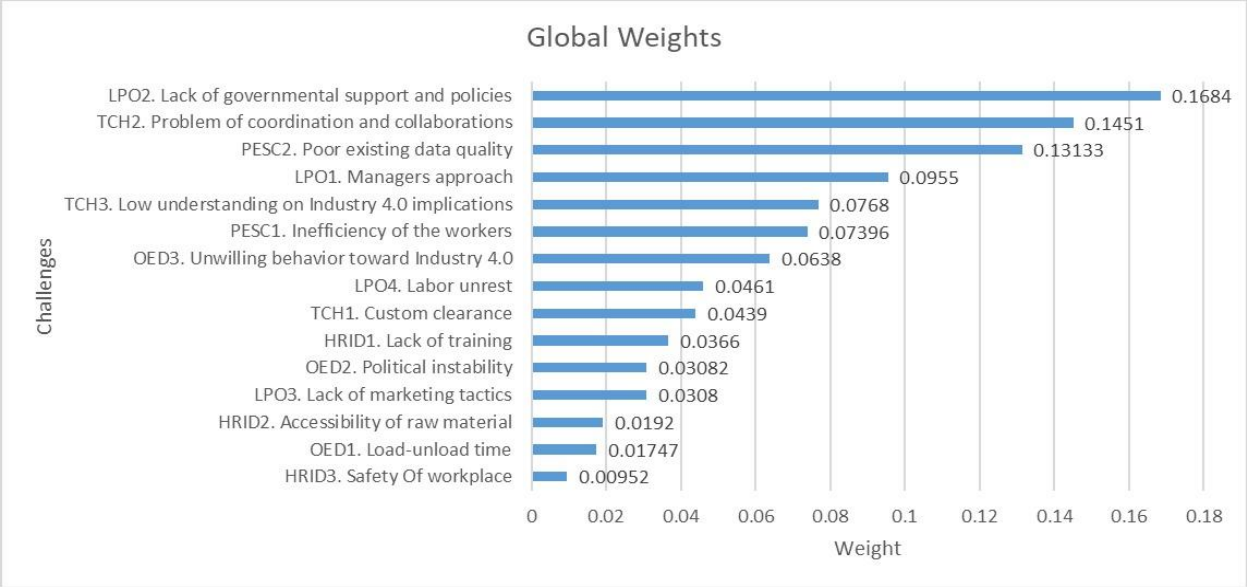


Figure 4. Global weights of each challenge by Fuzzy AHP

quantified the relative urgency of each challenge and provided actionable insights for policymakers and industry stakeholders. By distinguishing strategic priorities from operational constraints, the analysis offers a nuanced roadmap for sustainable supply chain transformation in the RMG sector. Additionally, the methodological rigor of the FAHP framework provided priorities that are theoretically and practically robust, which can serve as a foundation for targeted interventions in the adoption of Industry 4.0 in anywhere in the world.

3.5. BEST-WORST METHOD (BWM)

In this section, the Best-Worst Method (BWM) has been employed to systematically evaluate and prioritize the challenges hindering Industry 4.0 adoption in Bangladeshi RMG sector. The methodology began with selecting the most and least important criteria through expert judgment. From expert consensus, LPO was designated as the best (most critical) criterion and HRID as the worst (least critical). Pairwise comparisons were then conducted using a 9-point scale to assess the relative importance of the best criterion against others (Best-to-Others) and all criteria against the worst criterion (Others-to-Worst). These comparisons facilitated the calculation of optimal weights for each criterion. Subsequently, the same BWM procedure was applied to determine weights for sub-challenges within each main criterion. The final step involved computing global weights by combining the main criterion weights with their respective sub-criterion weights, yielding a comprehensive ranking of all challenges. **Figure 5** shows the flowchart of the proposed BWM study. The motivation behind this approach, lies in highlighting the predominance of policy and leadership issues while offering actionable insights for stakeholders in the RMG sector. The ability of BWM to handle subjective judgments with minimal pairwise comparisons made it particularly suitable for this complex, multi-faceted decision-making problem.

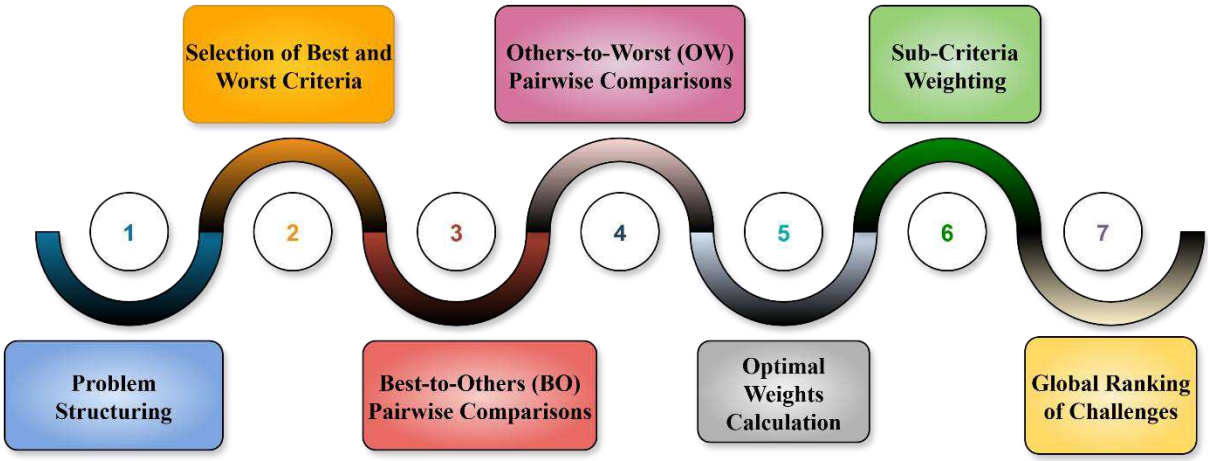


Figure 5. Roadmap of the proposed BWM method

3.5.1. Problem Structuring

The study began by defining the decision-making framework through a structured identification of key challenges. As shown in **Table 3**, five primary challenge dimensions of Industry 4.0 adoption barriers in the RMG sector has been defined as, Leadership and Policy Obstacles (LPO), Human Resource and Infrastructure Deficiencies (HRID), Trade and Collaboration Hurdles (TCH), Operational and Environmental Disruptions (OED), and Production Efficiency and Sustainability Concerns (PESC). **Table 19** shows the defined criterions for initializing BWM analysis. Each criterion encompassed specific sub-challenges, resulting in a comprehensive set of factors.

Table 19 Primary challenge dimensions defined as criterion

Criterion Number = 05	Criterion1	Criterion2	Criterion3	Criterion4	Criterion5
Name of the Criterion	Leadership and Policy Obstacles (LPO)	Human Resource and Infrastructure Deficiencies (HRID)	Trade and Collaboration Hurdles (TCH)	Operational and Environmental Disruptions (OED)	Production Efficiency and Sustainability Concerns (PESC)

3.5.2. Selection of Best and Worst Criteria

To streamline the evaluation process, the most and least significant criteria were identified through expert judgment. Leadership and Policy Obstacles (LPO) were unequivocally designated as the best (most critical) criterion. Conversely, Human Resource and Infrastructure Deficiencies (HRID) were selected as the worst (least critical) criterion, indicating their relatively lower immediate impact. This strategic selection reduced comparison complexity while preserving the integrity of the decision hierarchy.

3.5.3. Best-to-Others (BO) Pairwise Comparisons

The relative importance of the best criterion (LPO) over all other criteria was assessed by expert judgement using a 9-point scale, where higher values indicated greater dominance. Subject matter experts provided cardinal judgments in quantifying the relative dominance of the best criterion (LPO) over each alternative

criterion. These method transforms qualitative perceptions into quantifiable ratios and captured the intensity of inter-criteria relationships. The process mathematically represents the importance of LPO across the framework. **Table 20** represents this comparison.

Table 20 Comparing most critical criterion among all other criterion

Best to Others	Leadership and Policy Obstacles (LPO)	Human Resource and Infrastructure Deficiencies (HRID)	Trade and Collaboration Hurdles (TCH)	Operational and Environmental Disruptions (OED)	Production Efficiency and Sustainability Concerns (PESC)
Leadership and Policy Obstacles (LPO)	1	7	2	4	3

3.5.4. Step 4: Others-to-Worst (OW) Pairwise Comparisons

Complementing the BO analysis, the Others-to-Worst comparisons establish a dual reference framework by evaluating all criteria against the worst criterion, in this case, HRID. This bidirectional assessment strategy serves as a methodological safeguard by enhancing the reliability of derived weights. **Table 21** represents the assessments of others-to-worst vectors.

Table 21 Comparing worst criterion among all other criterion

Others to the Worst	Human Resource and Infrastructure Deficiencies (HRID)
Leadership and Policy Obstacles (LPO)	7
Human Resource and Infrastructure Deficiencies (HRID)	1
Trade and Collaboration Hurdles (TCH)	4
Operational and Environmental Disruptions (OED)	2
Production Efficiency and Sustainability Concerns (PESC)	3

3.5.5. Optimal Weights Calculation

The analytical core of the study employed advanced linear programming (LP) formulation to derive optimal criterion weights. The optimization model minimized the maximum absolute deviation between the ratio-based preference judgments and computed weight ratios. It is mathematically expressed as a minmax problem. This formulation ensured the closest possible alignment between expert judgments and derived weights.

The minmax formula goes by **Equation 9,**

$$minmax\left\{\left|\frac{WB}{Wj} - aBj\right| , \left|\frac{wj}{wW} - ajW\right|\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

To solve this, we convert the minmax problem into a Linear Program (LP) by introducing a slack variable, ξ. In order to calculate Best to others and Worst to other consistency, **Equation 10** and **Equation 11** were used.

$$\left|\frac{WB}{Wj} - aBj\right| \leq \xi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

$$\left|\frac{wj}{wW} - ajW\right| \leq \xi \quad \text{..... (11)}$$

After solving the LP problem through mathematical calculation, the obtained optimal weights for all criterion are shown in **Table 22.**

Table 22 Optimal weights of all criterion

Name of the Criterion	Leadership and Policy Obstacles (LPO)	Human Resource and Infrastructure Deficiencies (HRID)	Trade and Collaboration Hurdles (TCH)	Operational and Environmental Disruptions (OED)	Production Efficiency and Sustainability Concerns (PESC)
Weights	0.4391	0.0593	0.2314	0.1157	0.1543

It is evident from the table that LPO (43.91%) and TCH (23.14%) are the dominating criterion in the challenge landscape.

3.5.6. Sub-Criteria Weighting

The analytical depth expanded through recursive application of the BWM to sub-criteria within each principal dimension. The process yielded localized weight structures that captured the intricate priority gradients within each challenge category. **Table 23** shows the weights of each sub-challenges.

Table 23 Weights of all sub criterion

Main Dimension	Sub-Challenges	Weights
Leadership and Policy Obstacles (LO)	Managers' approach (LPO1)	0.203
	Lack of governmental support and policies (LPO2)	0.559
	Lack of marketing tactics (LPO3)	0.084
	Labor unrest (LPO4)	0.152
Human Resource and Infrastructure Deficiencies (HRID)	Lack of training (HRID1)	0.61
	Accessibility of raw material (HRID2)	0.24
	Safety of workplace (HRID3)	0.13
Trade and Collaboration Hurdles (TCH)	Custom clearance (TCH1)	0.205
	Problem of coordination and collaborations (TCH2)	0.48
	Low understanding of Industry 4.0 implications (TCH3)	0.303
Operational and Environmental Disruptions (OED)	Load-unload time (OED1)	0.123
	Political instability (OED2)	0.28
	Unwilling behavior toward Industry 4.0 (OED3)	0.594
Production Efficiency and Sustainability Concerns (PESC)	Inefficiency of workers (PESC1)	0.333
	Poor existing data quality (PESC2)	0.667

This consolidated table provides a comprehensive view of the challenge hierarchy. For example, within the main challenge dimension LPO, Lack of governmental support and policies (LPO2) is scored at 55.9%, outweighing managerial issues. Thus, it enables the policymakers to prioritize interventions effectively.

3.5.7. Step 7: Global Ranking of Challenges

Finally, the analytical culmination synthesized local and global priority structures through multiplicative aggregation of criterion and sub-criterion weights. The global weight of a sub-challenge is computed as:

Global Weight = (Global Weight of Main Dimension) × (Local Weight of Sub-Challenge)

This integration produced a comprehensive ranking of all sub-challenges by global importance. It also mathematically represents their aggregate impact on Industry 4.0 adoption. The final prioritization of challenges presented in **Table 24** reveals critical insights into the sector's most pernicious barriers while identifying potentially tractable intervention points. The ranking's methodological robustness stemmed from its foundation in optimized weight derivation and hierarchical aggregation. Overall, the ranking collectively demonstrates a state-of-the-art application of multi-criteria decision analysis to industrial policy challenges.

Table 24 Ranking of challenges to Industry 4.0 initiatives for sustainability orientation

Main Dimensions	Relative weights	Sub challenges	Relative weights	Relative rankings	Global weights	Global rankings
Leadership and Policy Obstacles (LPO)	0.4391	Managers approach (LPO 1)	0.203	2nd	0.0891	4th
		Lack of governmental support and policies (LPO 2)	0.559	1st	0.2454	1st
		Lack of marketing tactics (LPO 3)	0.084	4th	0.0368	10th
		Labor unrest (LPO 4)	0.152	3rd	0.0667	7th
Human Resource and Infrastructure Deficiencies (HRID)	0.0593	Lack of training (HRID 1)	0.61	1st	0.03617	11th
		Accessibility of raw material (HRID 2)	0.24	2nd	0.014232	13th
		Safety Of workplace (HRID 3)	0.13	3rd	0.0077	15th
Trade and Collaboration Hurdles(TCH)	0.2314	Custom clearance (TCH1)	0.205	3rd	0.04743	9th
		Problem of coordination and collaborations (TCH 2)	0.48	1st	0.11107	2nd
		Low understanding on Industry 4.0 implications (TCH 3)	0.303	2nd	0.07011	5th
Operational and Environmental Disruptions(OED)	0.1157	Load-unload time (OED 1)	0.123	3rd	0.014231	14th
		Political instability (OED 2)	0.28	2nd	0.03239	12th
		Unwilling behavior toward Industry 4.0 (OED 3)	0.594	1st	0.0687	6th
Production Efficiency and	0.1543	Inefficiency of the workers (PESC 1)	0.333	2nd	0.0513	8th

Sustainability Concerns (PESC)	Poor existing data quality (PESC 2)	0.667	1st	0.1029	3rd

The results in **Table 24** shows that Policy and governance is the top barrier in the adoption of Industry 4.0 in the RMG sector of Bangladesh. Coordination failures and data quality follow closely. Accordingly, Infrastructure/training (HRID) has the least impact. Therefore, it can be concluded that governments must address regulatory gaps (LPO2) and inter-firm collaboration (TCH2). Additionally, Investment in data systems (PESC2) and worker training (HRID1) can also be considered as important operational action plans. **Figure 6** graphically depicts the global weights derived by BWM method.

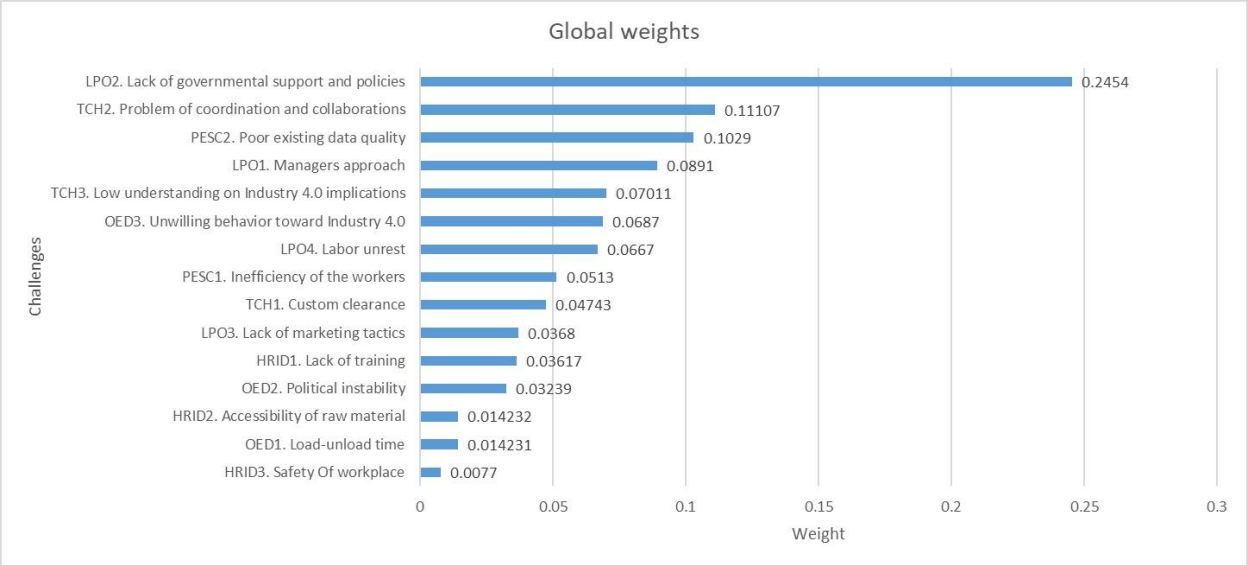


Figure 6. Graphical representation of global weights of challenges by BWM

Overall, the methodological architecture of the study demonstrated how sophisticated decision analysis techniques can illuminate complex industrial modernization challenges. By systematically transforming expert judgments into quantifiable priorities, the research provides both theoretical and practical contributions to understanding Industry 4.0 adoption barriers in developing economy contexts. The approach set a precedent for similar studies in industrial policy and technological transition analysis.

4. Results and Discussion

The study looks into 15 challenges in Bangladeshi RMG sector, which are divided into five categories: Leadership and Policy Obstacles (LPO), Human Resource and Infrastructure Deficiencies (HRID), Trade and Collaboration Obstacles (TCH), Operational and Environmental Disruptions (OED), and Production Efficiency and Sustainability Concerns (PESC). The comprehensive application of both Fuzzy AHP (FAHP) and Best-Worst Method (BWM) provided robust and complementary insights into these challenges that are hindering Industry 4.0 adoption. The ranking of the challenges obtained from FAHP and BWM methods are illustrated in **Table 25** and **Table 26** respectively.

The integrated analysis revealed several critical findings that can guide strategic interventions. Both methods unequivocally identify Lack of governmental support and policies (LPO) as the foremost obstacle. Problem of coordination and collaborations and Poor existing data quality follows the second and third place respectively, in both methods. This tripartite consensus at the apex of the rankings underscores that

strategic, external, and systemic barriers are perceived as more formidable than internal operational ones. Similarly, at the lower end of the spectrum, both techniques rank accessibility of raw material, Load-unload time, and Safety of workplace as the three least critical challenges. It suggests that while these are present, they are not considered primary impediments to adoption.

However, the divergence in the mid-tier rankings provides nuanced insights into the methodological strengths of each approach. For instance, Inefficiency of the workers is ranked 6th by FAHP but 8th by BWM, while Unwilling behavior toward Industry 4.0 is ranked 7th by FAHP and 6th by BWM. This minor discrepancy highlights how the fuzzy logic of FAHP weighs certain human-centric barriers slightly differently than the crisp, optimization-based BWM. Furthermore, Lack of training is ranked 10th by FAHP but 11th by BWM, and Lack of marketing tactics is ranked 12th by FAHP but 10th by BWM. These variations, though not drastic, suggest the BWM method relies on direct best-to-worst comparisons, whereas FAHP's comprehensive pairwise comparisons retain more granularity in mid-tier challenges.

The overall high correlation between the two rankings validates the robustness of the identified challenge hierarchy. Together, they provide a comprehensive and validated roadmap for industry leaders, ensuring that strategic efforts are directed toward the most impactful barriers first.

Table 25 Ranking the challenges through the Fuzzy AHP method

Challenges to Industry 4.0diffusion to achieve sustainability in the supply chain for RMG industry	Ranking by FAHP
Lack of governmental support and policies	1st
Problem of coordination and collaborations	2nd
Poor existing data quality	3rd
Managers approach	4th
Low understanding on Industry 4.0 implications	5th
Inefficiency of the workers	6th
Unwilling behavior toward Industry 4.0	7th
Labor unrest	8th
Custom clearance	9th
Lack of training	10th
Political instability	11th
Lack of marketing tactics	12th
Accessibility of raw material	13th
Load-unload time	14th
Safety Of workplace	15th

Table 26 Ranking the challenges through the Fuzzy BWM method

Challenges to Industry 4.0 diffusion to achieve sustainability in the supply chain for RMG industry	Ranking
Lack of governmental support and policies	1st
Problem of coordination and collaborations	2nd
Poor existing data quality	3rd

Managers approach	4th
Low understanding on Industry 4.0 implications	5th
Unwilling behavior toward Industry 4.0	6th
Labor unrest	7th
Inefficiency of the workers	8th
Custom clearance	9th
Lack of marketing tactics	10th
Lack of training	11th
Political instability	12th
Accessibility of raw material	13th
Load-unload time	14th
Safety Of workplace	15th

5. Strategic Policy Recommendations

Based on these findings, a multi-tiered policy approach is recommended:

5.1. Policy and Governance Reforms (Immediate Priority)

a) Establish a dedicated Industry 4.0 task force within the Ministry to develop and implement a comprehensive digital transformation roadmap.

b) Introduce fiscal incentives for IoT investments and accelerated depreciation for smart manufacturing equipment.

c) Streamline regulatory processes for technology imports and reduce bureaucratic hurdles for digital initiatives

5.2. Collaborative Ecosystem Development (Medium-term)

a) Industries can be clustered with shared digital infrastructure to overcome coordination challenges.

b) Develop public-private partnerships for technology demonstration centers.

c) Implement standardized data protocols across the supply chain to enable interoperability

5.3. Workforce Transformation (Long-term)

a) Redesign vocational training curriculum, inspired by the dual-education model existing in the developed countries.

b) Establish sector-specific digital skills certification programs.

c) Develop targeted upskilling initiatives focusing on data analytics and IoT maintenance.

5.4. Implementation Roadmap

The global ranking of the barriers suggests that the phased implementation should begin with immediate policy interventions. Meanwhile, ecosystem development initiatives can take place, while continuing workforce development as a long-term ongoing process.

6. Conclusion

This study has systematically identified and prioritized the barriers to integrating Industry 4.0 for Sustainable Supply Chain Management (SSCM) in the RMG sector of Bangladesh. The framework combining Fuzzy AHP and the Best-Worst Method (BWM) has yielded a hierarchy of impediments. The most salient finding to emerge from this analysis is the identification of Leadership and Policy Obstacles as the paramount barrier- a challenge that surpasses even financial and technological constraints. This underscores that the primary challenge is not a lack of technical solutions or capital, but rather a deficit in strategic direction, governance, and supportive institutional frameworks.

The research successfully answers its core questions. It identifies 15 critical barriers and clusters them into five dimensions, providing a deeper understanding of adoption challenges. Methodologically, it demonstrates that the combination of FAHP and BWM offers superior robustness through cross-validation.

The derived strategic roadmap presents a clear call to action. For policymakers, the immediate priority must be to bridge the institutional void by establishing national digital industrial policies. For industry leaders, the imperative is to foster collaboration, invest in data infrastructure, and initiate workforce transformation.

While contextualized within the Bangladeshi RMG sector, the methodological framework and the fundamental insight are directly transferable. This study thus provides a replicable blueprint for other labor-intensive industries in emerging economies. The journey toward a Industry 4.0 enabled, sustainable RMG sector needs a strategic transformation, and this research provides the essential map for that journey.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets generated and analysed during the current study (anonymized survey responses, expert pairwise-comparison matrices, best-to-others and others-to-worst comparison vectors, and the computed Fuzzy AHP and BWM weights) are not publicly available because they were collected under a confidentiality assurance given to the participating experts and their organizations, but they are available from the corresponding author (Sayef Ahmed, sayefsowro@gmail.com) on reasonable request.

Ethics declaration

All methods were carried out in accordance with relevant guidelines and regulations. All experimental protocols were approved .

Informed consent was obtained from all subjects, including all industry experts whose opinions were used to validate and weight the barriers, prior to their participation in the study.

Author contributions

M.W.H.: Conceptualization, Methodology, Investigation (data collection), Formal analysis, Visualization, Writing – original draft. S.A.: Conceptualization, Methodology, Validation, Supervision, Project administration, Writing – review and editing. All authors reviewed and approved the final manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

7. REFERENCES

Ahmed, S. S., Akter, T., & Ma, Y. (2018). Green Supply Chain Management (GSCM) Performance Implemented by the Textile Industry of Gazipur District, Dhaka. *Logistics*, *2*(4), 21. https://doi.org/10.3390/logistics2040021

Alshbili, I., Elamer, A. A., & Moustafa, M. W. (2021). Social and environmental reporting, sustainable development and institutional voids: Evidence from a developing country. *Corporate Social Responsibility and Environmental Management*, *28*(2), 881–895. https://doi.org/10.1002/csr.2096

Aziz, F., Siam, S. A. J., Fuad, M. N., & Mahbub, M. Bin. (2023). *Exploring the Dynamics of Sustainable Supply Chain Practices in the Textile Industry from Bangladesh Context*. https://doi.org/https://doi.org/10.26480/csmj.02.2024.32.36

Aziz Khan, M. M., Alam, M. J., Saha, S., & Sayem, A. (2024). Critical barriers to adopt sustainable manufacturing practices in medium-sized ready-made garment manufacturing enterprises and their mitigation strategies. *Heliyon*, *10*(20), e39195. https://doi.org/10.1016/j.heliyon.2024.e39195

Bag, S., Wood, L. C., Telukdarie, A., & Venkatesh, V. G. (2023). Application of Industry 4.0 tools to empower circular economy and achieving sustainability in supply chain operations. *Production Planning & Control*, *34*(10), 918–940. https://doi.org/10.1080/09537287.2021.1980902

Bai, C., Dallasega, P., Orzes, G., & Sarkis, J. (2020). Industry 4.0 technologies assessment: A sustainability perspective. *International Journal of Production Economics*, *229*, 107776. https://doi.org/10.1016/j.ijpe.2020.107776

Bai, C., Quayson, M., & Sarkis, J. (2022). Analysis of Blockchain's enablers for improving sustainable supply chain transparency in Africa cocoa industry. *Journal of Cleaner Production*, *358*(April), 131896. https://doi.org/10.1016/j.jclepro.2022.131896

Bair, J., Anner, M., & Blasi, J. (2020). The political economy of private and public regulation in post-Rana Plaza Bangladesh. *Ilr Review*, *73*(4), 969–994.

Bala, B. K., Islam, M. M., Ghosh, S., Hossain, M. S., Hoque, A. S. M. M., & Saha, S. (2020). Modelling of supply chain of ready-made garments in Bangladesh. *Systems Research and Behavioral Science*, *37*(1), 38–55. https://doi.org/10.1002/sres.2575

Balamurugan, S., Ayyasamy, A., & Joseph, K. S. (2022). IoT-Blockchain driven traceability techniques for improved safety measures in food supply chain. *International Journal of Information Technology*, *14*(2), 1087–1098. https://doi.org/10.1007/s41870-020-00581-y

Barua, U., & Ansary, M. A. (2017). Workplace safety in Bangladesh ready-made garment sector: 3 years after the Rana Plaza collapse. *International Journal of Occupational Safety and Ergonomics*, *23*(4), 578–583. https://doi.org/10.1080/10803548.2016.1251150

Bhattacharya, D., Rahman, M., & Raihan, A. (2002). Contribution of the RMG Sector to the Bangladesh Economy. *CPD*

Occasional Paper Series, *50*(6), 1–26.

Biswas, D., Jalali, H., Ansaripoor, A. H., & De Giovanni, P. (2023). Traceability vs. sustainability in supply chains: The implications of blockchain. *European Journal of Operational Research*, *305*(1), 128–147. https://doi.org/10.1016/j.ejor.2022.05.034

Bonekamp, L., & Sure, M. (2015). Consequences of Industry 4.0 on human labour and work organisation. *Journal of Business and Media Psychology*, *6*(1), 33–40.

C. L., K., & M., S. (2016). A Case Study on Constraints Affecting the Productivity of Readymade Garment (RMG) Industry in Bangladesh. *International Journal of Managing Value and Supply Chains*, *7*(3), 69–78. https://doi.org/10.5121/ijmvsc.2016.7305

Calabrese, A., Levialdi Ghiron, N., & Tiburzi, L. (2021). 'Evolutions' and 'revolutions' in manufacturers' implementation of industry 4.0: a literature review, a multiple case study, and a conceptual framework. *Production Planning & Control*, *32*(3), 213–227. https://doi.org/10.1080/09537287.2020.1719715

Chabba, S., Matthews, G. F., & Netravali, A. N. (2005). 'Green' composites using cross-linked soy flour and flax yarns. *Green Chemistry*, *7*(8), 576. https://doi.org/10.1039/b410817e

Chamekh, M., Asmi, S. El, Hamdi, M., & Kim, T.-H. (2018). IoT Based Tracking System For Supply Chain Management. *2018 6th International Conference on Wireless Networks and Mobile Communications (WINCOM)*, 1–5. https://doi.org/10.1109/WINCOM.2018.8629607

Cheng, E. W. L., Li, H., & Ho, D. C. K. (2002). Analytic hierarchy process (AHP). *Measuring Business Excellence*, *6*(4), 33–37. https://doi.org/10.1108/13683040210451697

Chowdhury, A. Y., Islam, N., & Alam, M. Z. (2019). Impediments of Supply Chain Management Application in Readymade Garments Industry of Bangladesh. *Journal of Business and Social Sciences Research*, *4*(1), 1–12. https://doi.org/10.3126/jbssr.v4i1.28989

Chowdhury, M., Ahmed, R., & Yasmin, M. (2014). Prospects and Problems of RMG Industry: A study on Bangladesh. *Prospects*, *5*(7), 103–118.

Chowdhury, N. A., Ali, S. M., Mahtab, Z., Rahman, T., Kabir, G., & Paul, S. K. (2019). A structural model for investigating the driving and dependence power of supply chain risks in the readymade garment industry. *Journal of Retailing and Consumer Services*, *51*(June 2019), 102–113. https://doi.org/10.1016/j.jretconser.2019.05.024

Chowdhury, R. S., Uddin, S. M. S., Islam, S., & Alam, M. S. (2022). Impact of COVID-19 on the Ready-Made Garments Industry of Bangladesh. In *Towards a Sustainable Economy* (pp. 74–95). Routledge.

Çiğdem, Ş., Meidute-Kavaliauskiene, I., & Yıldız, B. (2023). Industry 4.0 and Industrial Robots: A Study from the Perspective of Manufacturing Company Employees. *Logistics*, *7*(1), 17. https://doi.org/10.3390/logistics7010017

Cimini, C., Boffelli, A., Lagorio, A., Kalchschmidt, M., & Pinto, R. (2020). How do industry 4.0 technologies influence organisational change? An empirical analysis of Italian SMEs. *Journal of Manufacturing Technology Management*, *32*(3), 695–721. https://doi.org/10.1108/JMTM-04-2019-0135

Dalal, S., Lilhore, U. K., Simaiya, S., Radulescu, M., & Belascu, L. (2024). Improving efficiency and sustainability via supply chain optimization through CNNs and BiLSTM. *Technological Forecasting and Social Change*, *209*(October), 123841. https://doi.org/10.1016/j.techfore.2024.123841

Debnath, B., Siraj, M. T., Rashid, K. H. O., Mainul Bari, A. B. M., Karmaker, C. L., & Aziz, R. Al. (2023). Analyzing the critical success factors to implement green supply chain management in the apparel manufacturing industry: Implications for sustainable development goals in the emerging economies. *Sustainable Manufacturing and Service Economics*, *2*, 100013. https://doi.org/10.1016/j.smse.2023.100013

Dong, C., & Li, D. (2025). Achieving Economic and Environmental Sustainability With Supply Chain Contracts. *Production and Operations Management*, *34*(7), 1632–1649. https://doi.org/10.1177/10591478241303661

Getawa Ayalew, G., Admasu Alemneh, L., & Melkamu Ayalew, G. (2024). Exploring fuzzy AHP approaches for quality management control practices in public building construction projects. *Cogent Engineering*, *11*(1), 2326765. https://doi.org/10.1080/23311916.2024.2326765

Habib, M. A., Balasubramanian, S., Shukla, V., Chitakunye, D., & Chanchaichujit, J. (2022). Practices and performance outcomes of green supply chain management initiatives in the garment industry. *Management of Environmental Quality: An International Journal*, *33*(4), 882–912. https://doi.org/10.1108/MEQ-08-2021-0189

Haddud, A., DeSouza, A., Khare, A., & Lee, H. (2017). Examining potential benefits and challenges associated with the Internet of Things integration in supply chains. *Journal of Manufacturing Technology Management*, *28*(8), 1055–1085. https://doi.org/10.1108/JMTM-05-2017-0094

Haque, A. (2009). Lead time management in the garment sector of Bangladesh: an avenues for survival and growth. *European Journal of Scientific Research*, *33*(4), 617–629.

Hasan, M. (2017). Supply Chain Management in Readymade Garments Industry, Bangladesh. *Asian Business Review*, *7*(3), 103–110. https://doi.org/10.18034/abr.v7i3.18

Hasan, M. M., Hossain, I., Hassan, M., & Hridoy, M. W. (2025). Design and Development of a Compact Automated Parking System: Integration of Vertical Rotary Mechanism and <scp>IoT</scp> Interface. *Engineering Reports*, *7*(8), e70299. https://doi.org/10.1002/eng2.70299

Hasan, M. Z., Ghosh, J., & Chakrabortty, A. (2020). IDENTIFICATION OF THE SIGNIFICANCE AND RELEVANT BARRIERS OF SUSTAINABILITY ASPECTS AT THE WORKERS' LEVEL IN THE GARMENTS INDUSTRY OF BANGLADESH. *International Journal of Innovative Research in Engineering & Management*, *7*(6), 68–77. https://doi.org/10.21276/ijirem.2020.7.6.1

Hemphill, T. A., & White, G. O. (2018). Multinational Enterprises, Employee Safety and the Socially Responsible Supply Chain: The Case of Bangladesh and the Apparel Industry. *Business and Society Review*, *123*(3), 489–528. https://doi.org/10.1111/basr.12153

Ho, W. (2008). Integrated analytic hierarchy process and its applications – A literature review. *European Journal of Operational Research*, *186*(1), 211–228. https://doi.org/10.1016/j.ejor.2007.01.004

Horner, J., & Ryan, P. (2019). Blockchain Standardsfor Sustainable Development. *Journal of ICT Standardization*, *7*(3), 225–

248. https://doi.org/10.13052/jicts2245-800X.733

Hossain, M., Aziz, R. Al, Karmaker, C. L., Debnath, B., Bari, A. B. M. M., & Islam, A. R. M. T. (2024). Exploring the barriers to implement industrial symbiosis in the apparel manufacturing industry: Implications for sustainable development. *Heliyon*, *10*(13), e34156. https://doi.org/10.1016/j.heliyon.2024.e34156

Hossain, M. I., Rabbi, M. S., & Ali, M. T. (2025). Shape memory alloys in modern engineering: progress, problems, and prospects. *RSC Advances*, *15*(40), 33046–33100. https://doi.org/10.1039/D5RA04560F

Hossain, N. (2019). Rana Plaza, disaster politics, and the empowerment of women garment workers in Bangladesh. *Contemporary South Asia*, *27*(4), 516–530. https://doi.org/10.1080/09584935.2019.1683719

Hossian, M. S., Kabir, R., & Latifee, E. H. (2019). Export Competitiveness of Bangladesh Readymade Garments Sector. *International Journal of Research in Business and Social Science (2147- 4478)*, *8*(3), 45–63. https://doi.org/10.20525/ijrbs.v8i3.205

Ipaki, B., & Hosseini, Z. (2025). Repair-oriented design and manufacturing strategies for circular electronic products, from mass customization/standardization to scalable repair economy. *Results in Engineering*, *25*, 104169. https://doi.org/10.1016/j.rineng.2025.104169

Islam, M. A., Jantan, A. H., Hashim, H., Chong, C. W., Abdullah, M. M., & Abdul Hamid, A. B. (2018). Fourth industrial revolution in developing countries: A case on Bangladesh. *Journal of Management Information and Decision Sciences (JMIDS)*, *21*(1).

Islam, S., Abdul Hannan Mia, M., & Zoynal Abedin, M. (2022). Evaluation of Causes and Effects of Fire and Other Safety Incidents in Readymade Garment Industry of Bangladesh. *American Journal of Mechanical and Industrial Engineering*, *7*(2), 13. https://doi.org/10.11648/j.ajmie.20220702.11

Islam, T., & Halim, M. A. (2022). Impact of ready-made garments (RMG) industries and sustainability: Perspective of the pandemic period in developing country. *Cleaner Engineering and Technology*, *11*, 100567. https://doi.org/10.1016/j.clet.2022.100567

Kabir, H., Maple, M., & Usher, K. (2021). The impact of COVID-19 on Bangladeshi readymade garment (RMG) workers. *Journal of Public Health*, *43*(1), 47–52. https://doi.org/10.1093/pubmed/fdaa126

Kamble, S. S., Gunasekaran, A., Parekh, H., Mani, V., Belhadi, A., & Sharma, R. (2022). Digital twin for sustainable manufacturing supply chains: Current trends, future perspectives, and an implementation framework. *Technological Forecasting and Social Change*, *176*(November 2020), 121448. https://doi.org/10.1016/j.techfore.2021.121448

Karmaker, C. L., Aziz, R. Al, Ahmed, T., Misbauddin, S. M., & Moktadir, M. A. (2023). Impact of industry 4.0 technologies on sustainable supply chain performance: The mediating role of green supply chain management practices and circular economy. *Journal of Cleaner Production*, *419*, 138249. https://doi.org/10.1016/j.jclepro.2023.138249

Kayikci, Y., Kazancoglu, Y., Gozacan-Chase, N., & Lafci, C. (2022). Analyzing the drivers of smart sustainable circular supply chain for sustainable development goals through stakeholder theory. *Business Strategy and the Environment*, *31*(7), 3335–3353. https://doi.org/10.1002/bse.3087

Khondkar, M., & Honey, S. (2022). SUSTAINABLE MARKETING IN THE READY-MADE GARMENTS (RMG) SECTOR

OF BANGLADESH. *Indonesian Journal of Social Research (IJSR)*, *4*(2), 96–108. https://doi.org/10.30997/ijsr.v4i2.183

Kshetri, N. (2021). Blockchain and sustainable supply chain management in developing countries. *International Journal of Information Management*, *60*, 102376. https://doi.org/10.1016/j.ijinfomgt.2021.102376

Kumar, A., Moktadir, A., Liman, Z. R., Gunasekaran, A., Hegemann, K., & Rehman Khan, S. A. (2020). Evaluating sustainable drivers for social responsibility in the context of ready-made garments supply chain. *Journal of Cleaner Production*, *248*(April 2013), 119231. https://doi.org/10.1016/j.jclepro.2019.119231

Kumar, R., Singh, R. K., & Dwivedi, Y. K. (2020). Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: Analysis of challenges. *Journal of Cleaner Production*, *275*, 124063. https://doi.org/10.1016/j.jclepro.2020.124063

Li, Z., Liu, G., Liu, L., Lai, X., & Xu, G. (2017). IoT-based tracking and tracing platform for prepackaged food supply chain. *Industrial Management & Data Systems*, *117*(9), 1906–1916. https://doi.org/10.1108/IMDS-11-2016-0489

Lummus, R. R., Krumwiede, D. W., & Vokurka, R. J. (2001). The relationship of logistics to supply chain management: developing a common industry definition. *Industrial Management & Data Systems*, *101*(8), 426–432. https://doi.org/10.1108/02635570110406730

Majumdar, A., Garg, H., & Jain, R. (2021). Managing the barriers of Industry 4.0 adoption and implementation in textile and clothing industry: Interpretive structural model and triple helix framework. *Computers in Industry*, *125*, 103372. https://doi.org/10.1016/j.compind.2020.103372

Majumdar, A., Shaw, M., & Sinha, S. K. (2020). COVID-19 debunks the myth of socially sustainable supply chain: A case of the clothing industry in South Asian countries. *Sustainable Production and Consumption*, *24*, 150–155. https://doi.org/10.1016/j.spc.2020.07.001

Matemilola, S., Fadeyi, O., & Sijuade, T. (2020). Paris Agreement. In S. Idowu, R. Schmidpeter, N. Capaldi, L. Zu, M. Del Baldo, & R. Abreu (Eds.), *Encyclopedia of Sustainable Management* (pp. 1–5). Springer International Publishing. https://doi.org/10.1007/978-3-030-02006-4_516-1

McGrath, P., McCarthy, L., Marshall, D., & Rehme, J. (2021). Tools and Technologies of Transparency in Sustainable Global Supply Chains. *California Management Review*, *64*(1), 67–89. https://doi.org/10.1177/00081256211045993

Miller, D. (2012). *Last nightshift in Savar: The story of the spectrum sweater factory collapse*. McNidder and Grace Limited.

Moktadir, M. A., Ali, S. M., Rajesh, R., & Paul, S. K. (2018). Modeling the interrelationships among barriers to sustainable supply chain management in leather industry. *Journal of Cleaner Production*, *181*, 631–651. https://doi.org/10.1016/j.jclepro.2018.01.245

Nayal, K., Raut, R. D., Narkhede, B. E., Priyadarshinee, P., Panchal, G. B., & Gedam, V. V. (2023). Antecedents for blockchain technology-enabled sustainable agriculture supply chain. *Annals of Operations Research*, *327*(1), 293–337. https://doi.org/10.1007/s10479-021-04423-3

Nikseresht, A., Golmohammadi, D., & Zandieh, M. (2024). Sustainable green logistics and remanufacturing: a bibliometric analysis and future research directions. *The International Journal of Logistics Management*, *35*(3), 755–803. https://doi.org/10.1108/IJLM-03-2023-0085

Pereira, A. C., & Romero, F. (2017). A review of the meanings and the implications of the Industry 4.0 concept. *Procedia Manufacturing*, *13*, 1206–1214. https://doi.org/10.1016/j.promfg.2017.09.032

Praveen Kumar, Divya Choubey, Olamide Raimat Amosu, & Yewande Mariam Ogunsuji. (2024). AI-enhanced inventory and demand forecasting: Using AI to optimize inventory management and predict customer demand. *World Journal of Advanced Research and Reviews*, *23*(1), 1931–1944. https://doi.org/10.30574/wjarr.2024.23.1.2173

Rabbi, M. F., & Amin, M. Bin. (2024). Circular economy and sustainable practices in the food industry: A comprehensive bibliometric analysis. *Cleaner and Responsible Consumption*, *14*, 100206. https://doi.org/10.1016/j.clrc.2024.100206

Rahaman, T., & Islam, T. (2021). Impacts and Possible Responses Related to COVID-19 in the Textile and Apparel Industry of Bangladesh. *Journal of Management Science & Engineering Research*, *4*(2), 9–15. https://doi.org/10.30564/jmser.v4i2.3166

Rahman, M., & Anwar, A. (2006). *Bangladesh apparels export to the US market: an examination of her competitiveness vis-à-vis China*. Centre for Policy Dialogue Dhaka.

Raj, A., Dwivedi, G., Sharma, A., Lopes de Sousa Jabbour, A. B., & Rajak, S. (2020). Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. *International Journal of Production Economics*, *224*(August 2018), 107546. https://doi.org/10.1016/j.ijpe.2019.107546

Rashid, M. R., Ghosh, S. K., Alam, M. F. Bin, & Rahman, M. F. (2024). A fuzzy multi-criteria model with Pareto analysis for prioritizing sustainable supply chain barriers in the textile industry: Evidence from an emerging economy. *Sustainable Operations and Computers*, *5*, 29–40. https://doi.org/10.1016/j.susoc.2023.11.002

Rumi, M. H., Bala, S., Shah, A. M. M. M., Sayem, M. A., & Abedin, M. M. (2021). Future Tradeoff under Fourth Industrial Revolution in Bangladesh: A Study on RMG Sector. *International Journal of Social, Political and Economic Research*, *8*(1), 198–215. https://doi.org/10.46291/IJOSPERvol8iss1pp198-215

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology*, *15*(3), 234–281. https://doi.org/10.1016/0022-2496(77)90033-5

Saaty, T. L. (2013). Analytic Hierarchy Process. In S. I. Gass & M. C. Fu (Eds.), *Encyclopedia of Operations Research and Management Science* (pp. 52–64). Springer US. https://doi.org/10.1007/978-1-4419-1153-7_31

Saha, K. B., Rabbi, A. F. M. F., Nuruzzaman, M., & Mahmud, N. (n.d.). *Analyzing Raw Material Procurement Risk in the Supply Chain Management of Bangladeshi Readymade Garment Industry*. https://www.universepg.com/public/img/storage/journal-pdf/1739467923_Analyzing_raw_material_procurement_risk_in_the_supply_chain_management.pdf

Saha, P. K., Akhter, S., & Hassan, A. (2021). Framing Corporate Social Responsibility to Achieve Sustainability in Urban Industrialization: Case of Bangladesh Ready-Made Garments (RMG). *Sustainability*, *13*(13), 6988. https://doi.org/10.3390/su13136988

Said, N., Alrowais, R., Abdel-Daiem, M. M., & Mostafa, N. A. (2025). Bio-Waste to Bioenergy: Critical Assessment of Sustainable Energy Supply Chain in Egypt. *Resources*, *14*(8), 131. https://doi.org/10.3390/resources14080131

Sajja, G. S., Addula, S. R., Meesala, M. K., & Ravipati, P. (2025). Optimizing inventory management through AI-driven demand

forecasting for improved supply chain responsiveness and accuracy. *AIP Conference Proceedings*, *3306*(1), 050003. https://doi.org/10.1063/5.0275697

Salman, S., Hasanat, S., Rahman, R., & Moon, M. (2024). Analyzing the key barriers of adopting Industry 4.0 in Bangladesh's ready-made garment industry: an emerging economy example. *International Journal of Industrial Engineering and Operations Management*, *6*(3), 232–255. https://doi.org/10.1108/IJIEOM-04-2023-0034

Samad, M. A., Abdullah, J., & Rifat, M. A. H. (2023). Reduction of Manufacturing Lead Time by Value Stream Mapping of a Selected RMG Factory in Bangladesh. *Asian Journal of Engineering and Applied Technology*, *12*(1), 10–17. https://doi.org/10.51983/ajeat-2023.12.1.3578

Sazvar, Z., Tafakkori, K., Oladzad, N., & Nayeri, S. (2021). A capacity planning approach for sustainable-resilient supply chain network design under uncertainty: A case study of vaccine supply chain. *Computers & Industrial Engineering*, *159*(January 2020), 107406. https://doi.org/10.1016/j.cie.2021.107406

Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production*, *16*(15), 1699–1710. https://doi.org/10.1016/j.jclepro.2008.04.020

Sharma, K., Kumar, R., Kumar, A., Balabantaray, S., & Arora, M. (2023). A digital ecosystem for sustainable fruit supply chain in Uttarakhand: a comprehensive review. *Environment, Development and Sustainability*, *26*(5), 13217–13252. https://doi.org/10.1007/s10668-023-04142-8

Sharmin, S. (2022). IR 4.0 Readiness of Apparel Industry in Bangladesh. *Asian Journal of Social Sciences and Legal Studies*, *4*(4), 148–159. https://doi.org/10.34104/ajssls.022.01480159

Shekoohi Tolgari, F., & Zarrinpoor, N. (2024). A robust reverse pharmaceutical supply chain design considering perishability and sustainable development objectives. *Annals of Operations Research*, *340*(2–3), 981–1033. https://doi.org/10.1007/s10479-024-05871-3

Singh, M., & Pant, M. (2021). A review of selected weighing methods in MCDM with a case study. *International Journal of System Assurance Engineering and Management*, *12*(1), 126–144. https://doi.org/10.1007/s13198-020-01033-3

Stentoft, J., Adsbøll Wickstrøm, K., Philipsen, K., & Haug, A. (2021). Drivers and barriers for Industry 4.0 readiness and practice: empirical evidence from small and medium-sized manufacturers. *Production Planning & Control*, *32*(10), 811–828. https://doi.org/10.1080/09537287.2020.1768318

Stock, J. R., & Boyer, S. L. (2009). Developing a consensus definition of supply chain management: a qualitative study. *International Journal of Physical Distribution & Logistics Management*, *39*(8), 690–711. https://doi.org/10.1108/09600030910996323

Sumon, M. H., Shifa, N., & Gulrukh, S. (2017). Discourses of compensation and the normalization of negligence: the experience of the Tazreen factory fire. *Unmaking the Global Sweatshop: Health and Safety of the World's Garment Workers*, 147–172.

Tan, R. R., Aviso, K. B., Huelgas, A. P., & Promentilla, M. A. B. (2014). Fuzzy AHP approach to selection problems in process engineering involving quantitative and qualitative aspects. *Process Safety and Environmental Protection*, *92*(5), 467–475. https://doi.org/10.1016/j.psep.2013.11.005

Taqi, H. M. M., Ahmed, H. N., Paul, S., Garshasbi, M., Ali, S. M., Kabir, G., & Paul, S. K. (2020). Strategies to Manage the Impacts of the COVID-19 Pandemic in the Supply Chain: Implications for Improving Economic and Social Sustainability. *Sustainability*, *12*(22), 9483. https://doi.org/10.3390/su12229483

Yang, C.-C., & Chen, B.-S. (2004). KEY QUALITY PERFORMANCE EVALUATION USING FUZZY AHP. *Journal of the Chinese Institute of Industrial Engineers*, *21*(6), 543–550. https://doi.org/10.1080/10170660409509433

Zhang, A., Venkatesh, V. G., Wang, J. X., Mani, V., Wan, M., & Qu, T. (2023). Drivers of industry 4.0-enabled smart waste management in supply chain operations: a circular economy perspective in china. *Production Planning & Control*, *34*(10), 870–886. https://doi.org/10.1080/09537287.2021.1980909

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryFileS1ConsentFormv3.pdf