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RESEARCH PAPER

Supply chain performance in the age of Industry 4.0: evidence from manufacturing sector

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ABSTRACT

Goal: This study investigates the impact of Industry 4.0 adoption on supply chain performance in Bangladesh's manufacturing sector, emphasizing the mediating roles of digital supply chain integration, supply chain innovation, and supply chain visibility.

Design/methodology/approach: A quantitative research design was employed, utilizing a structured questionnaire distributed to 570 manufacturing professionals in Bangladesh, with 350 valid responses collected. Structural equation modeling (SEM) using SmartPLS was applied to analyze the data and test the hypothesized relationships.

Findings: The findings reveal that Industry 4.0 adoption significantly enhances digital supply chain integration (DSCI), supply chain innovation (SCI), and supply chain visibility (SCV), which collectively improve overall supply chain performance. Specifically, Industry 4.0 adoption strengthens DSCI by enabling real-time communication, reducing process fragmentation, and supporting more efficient decision-making. It also fosters SCI by driving innovative practices, adaptability, and continuous improvement within the supply chain. Furthermore, Industry 4.0 adoption improves SCV, enhancing traceability, transparency, and risk management. These mediating factors demonstrate the critical role of Industry 4.0 technologies in achieving superior supply chain outcomes.

Research limitations/implications: The study's limitations include the use of convenience sampling and data from a single industry sector within a developing country, which may limit the generalizability of the findings. Future research could explore additional variables and contexts to further validate these results.

Practical implications: The study provides actionable insights for manufacturing firms in developing economies on leveraging Industry 4.0 technologies to enhance supply chain performance. It also offers guidance for policymakers in supporting digital transformation initiatives.

Social implications: By highlighting the benefits of digital supply chain integration, the study contributes to broader societal goals of economic development and industrial competitiveness in emerging markets.

Originality/value: This study is among the first to empirically examine the impact of Industry 4.0 adoption on supply chain performance in Bangladesh, providing valuable insights for both practitioners and researchers.

Keywords: Industry 4.0; Supply Chain Performance; Digital Supply Chain Integration; Supply Chain Innovation; Supply Chain Visibility; Industry 5.0; Manufacturing Sector; Bangladesh.

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1 INTRODUCTION

Industry 4.0 (I 4.0) has revolutionized the global industrial sector through the integration of advanced digital technology. The transformative potential of Industry 4.0 lies in its ability to integrate digital and physical systems, driving unprecedented efficiency and innovation across industries. The operations and competition of companies are being significantly transformed by technologies such as the IoT, AI, big data analytics, and cyber-physical systems (Javaid *et al.*, 2023). 'I 4.0 optimises manufacturing efficiency and improves supply chain performance (SCP) via real-time data exchange, predictive analytics, and automation (Fatorachian & Kazemi, 2021; Khan *et al.*, 2024). The use of these technologies enables companies to swiftly address market needs, save operating expenses, and enhance overall supply chain agility and resilience (Belhadi *et al.*, 2022).

Although several industrialised nations have achieved considerable progress in the implementation of these technologies, the rate of 'I 4.0 adoption in developing countries such as Bangladesh is rather sluggish, mainly owing to infrastructural, financial, and knowledge limitations (Rahman *et al.*, 2022). The transformative potential of Industry 4.0 could address these limitations, offering a pathway for emerging economies to overcome traditional barriers and leapfrog into more competitive global positions. In the industrial sector of Bangladesh, 'I 4.0 has the capacity to markedly improve SCP, essential for sustaining competitiveness in the global market. Nonetheless, despite acknowledged advantages, there exists a paucity of empirical research examining the influence of 'I 4.0 implementation on SCP within Bangladesh's industrial sector. This research is especially pertinent after the COVID-19 pandemic, which has underscored the need for robust and flexible supply networks (Moosavi *et al.*, 2022).

The pandemic has expedited the global digital transformation of supply chains, rendering the deployment of 'I 4.0 technology more imperative. For Bangladeshi manufacturers, the use of these technologies might significantly transform their ability to address conventional supply chain difficulties, including delays, inefficiencies, and insufficient visibility, hence enhancing their competitive stance in the post-pandemic global market (Karmaker *et al.*, 2023; Khan & Emon, 2024). Created in 2011 as a plan to keep the industrial industry competitive via the use of digital technology, "Industry 4.0" originated in Germany (Fromhold-Eisebith *et al.*, 2021). It is defined by the integration of physical and digital systems, resulting in the establishment of networked smart factories capable of autonomous decision-making (Villalonga *et al.*, 2021). The fundamental technologies propelling 'I 4.0 include IoT, AI, machine learning, big data analytics, and cyber-physical systems, allowing real-time monitoring, predictive maintenance, and sophisticated process optimisation (Zonta *et al.*, 2020). The manufacturing industry in Bangladesh is a vital engine of economic development, accounting for over 20% of the nation's GDP and employing a substantial segment of the workforce (BBS, 2022). The ready-made garment (RMG) sector has established Bangladesh as a prominent global exporter. The industry has many obstacles, including poor productivity, insufficient infrastructure, and restricted technical capabilities, which impede its worldwide competitiveness (Abdul-Hamid *et al.*, 2020). The use of 'I 4.0 technology offers a solution to these difficulties by augmenting SCP via increased efficiency, transparency, and agility (Ghadge *et al.*, 2020). Notwithstanding the prospective advantages, the implementation of 'I 4.0 in Bangladesh has been constrained, since several enterprises continue to depend on conventional production methods (M. Rahman *et al.*, 2022). Insufficient awareness, elevated implementation costs, and inadequate technical proficiency are primary obstacles to adoption (Nnaji & Karakhan, 2020). The COVID-19 epidemic has shown weaknesses in the supply networks of several Bangladeshi firms, highlighting the need for digital transformation (M. R. Hossain *et al.*, 2022). In this context, it is essential to investigate the determinants affecting the adoption of 'I 4.0 technologies and their influence on SCP within the Bangladeshi manufacturing sector (MS).

The present condition of 'I 4.0 adoption in Bangladesh's MS is marked by an embryonic phase of digital transformation, with just a limited number of prominent enterprises actively investigating and using these technologies (Galletta *et al.*, 2022). Most manufacturing firms, especially small and medium-sized organisations (SMEs), persist in using conventional methods, exhibiting little investment in digital technology (Eller *et al.*, 2020). A recent survey by the Bangladesh Institute of Development Studies (BIDS) revealed that fewer than 10% of manufacturing firms in Bangladesh have implemented any form of 'I 4.0 technology, primarily basic automation and enterprise resource planning (ERP) systems (BIDS, 2022). The low adoption rate is a considerable worry because to competitive challenges from worldwide markets where digital transformation is rapidly becoming standard (Jayamaha *et al.*, 2024). The sluggish adoption of 'I 4.0 technology in the industrial industry may be ascribed to many issues. Initially, corporate executives exhibit insufficient knowledge and comprehension of the potential advantages and uses of new technologies (Ricci *et al.*, 2021). Moreover, the substantial initial expenditure required for the adoption of 'I 4.0 technologies is a significant obstacle, especially for SMEs with constrained

financial resources (Raj *et al.*, 2020). Thirdly, the sector has a deficiency of trained labour proficient in digital technologies, which obstructs the proper execution and use of ‘I 4.0 solutions (Peerally *et al.*, 2022). Notwithstanding these hurdles, indications of development are evident. The Bangladeshi government has acknowledged the significance of digital transformation and has initiated many programs to facilitate the adoption of ‘I 4.0 . The "Digital Bangladesh" strategy seeks to incorporate ICT into every facet of the economy, including manufacturing (Emon, 2023; M. Hossain, 2022). Furthermore, there are notable instances of successful ‘I 4.0 implementation in the RMG sector, where companies have used sophisticated robotics and AI-driven quality control systems to enhance production efficiency and minimise errors (Mohiuddin Babu *et al.*, 2022). These early adopters are establishing a benchmark for other companies in the field and illustrating the concrete advantages of ‘I 4.0 technology. In light of the present circumstances, there is an urgent want for empirical study to comprehend the effects of ‘I 4.0 implementation on SCP inside the Bangladeshi MS. This research seeks to fill this vacuum by elucidating the existing adoption levels, identifying the primary drivers and obstacles, and examining the impacts on supply chain efficiency, flexibility, and responsiveness. The manufacturing industry in Bangladesh is at a pivotal juncture, with substantial problems that jeopardise its long-term viability and competitiveness in the global market (M. M. Rahman, 2021). The business has historically depended on inexpensive labour and mass manufacturing; however, these benefits are diminishing due to increasing competition from nations swiftly embracing ‘I 4.0 technology (Javaid *et al.*, 2024). The absence of digital transformation in the Bangladeshi MS has led to inefficiencies, diminished efficiency, and insufficient supply chain visibility, impeding the industry's capacity to adapt to the changing needs of the global market (Akbari *et al.*, 2024; Emon & Khan, 2024). Notwithstanding the acknowledged promise of ‘I 4.0 to mitigate these difficulties, the adoption rate in Bangladesh remains low owing to many impediments, including elevated prices, insufficient technical competence, and poor awareness (Ahmed *et al.*, 2020). In this context, it is essential to comprehend how the implementation of ‘I 4.0 might improve SCP in the Bangladeshi MS. Current research has mostly concentrated on the technical dimensions of ‘I 4.0 , with little emphasis on its effects on SCP in poor nations such as Bangladesh (Rahman *et al.*, 2022). Furthermore, the distinctive obstacles encountered by Bangladeshi manufacturers, including infrastructural limitations and a lack of trained labour, have not been sufficiently examined in the literature (Hossian *et al.*, 2019).

The deficiency of knowledge is a substantial barrier to the extensive implementation of ‘I 4.0 technology within the industry. Consequently, this study seeks to investigate the following research enquiries: What is the present extent of ‘I 4.0 implementation in the Bangladeshi manufacturing sector? What are the primary facilitators and impediments to adoption? What is the effect of ‘I 4.0 adoption on SCP regarding efficiency, flexibility, and responsiveness? This study aims to elucidate the potential advantages and obstacles of ‘I 4.0 adoption in the Bangladeshi manufacturing sector, thereby aiding in the formulation of effective strategies for digital transformation within the industry. The primary objective of this study is to explore the impact of ‘I 4.0 adoption on SCP in the MS of Bangladesh. Specifically, the study aims to assess the current level of ‘I 4.0 adoption in the sector by identifying the extent to which digital technologies such as IoT, AI, big data analytics, and automation are being implemented (Emon *et al.*, 2023). It seeks to identify the key drivers and barriers influencing the adoption of these technologies, including factors such as cost, technical expertise, organizational readiness, and external pressures. Furthermore, the study aims to analyze the impact of ‘I 4.0 adoption on various dimensions of SCP, including efficiency, flexibility, responsiveness, and resilience. This work has significant implications for several reasons. It primarily fills a significant need in the literature by examining the effects of ‘I 4.0 implementation on SCP within the industrial sector of Bangladesh, a developing nation. The majority of current research on ‘I 4.0 has concentrated on industrialised nations, with little consideration of the distinct problems and possibilities encountered by emerging economies (Chauhan *et al.*, 2021). This research focusses on Bangladesh, offering significant insights into the contextual elements that affect the adoption of ‘I 4.0 technologies in a developing nation environment. Secondly, the research is important practically as it offers actual facts about the advantages and obstacles linked to the adoption of ‘I 4.0 by Bangladeshi enterprises. The results may assist corporate executives and policymakers in comprehending the possible effects of digital transformation on SCP, thereby guiding strategic choices regarding technology investment and implementation (Cezarino *et al.*, 2021). In light of escalating competitive pressures and the need for supply chain resilience in the post-pandemic context, these lessons have special significance for the industrial sector in Bangladesh (Mashalah *et al.*, 2022). Thirdly, the research enhances the current conversation on the digital transformation of Bangladesh's industrial sector. The report delineates the main facilitators and impediments to ‘I 4.0 adoption, providing a framework for expediting the sector's digital transition. This is essential for improving the sector's international competitiveness and advancing the nation's overarching economic development objectives (Mostafiz *et al.*, 2022). Furthermore, the study's results may inform the development of targeted interventions and capacity-building

programs to address the highlighted obstacles, including insufficient technical skills and elevated implementation costs (Cisneros-Montemayor *et al.*, 2019). The study's importance transcends the industrial sector, offering insights relevant to other sectors in Bangladesh and other emerging nations with analogous issues in digital transformation. This research elucidates how the implementation of 'I 4.0 might improve SCP, hence advancing the overarching objective of attaining sustainable and equitable industrial growth via digital innovation (Ward *et al.*, 2019). The transformative potential of Industry 4.0 underscores its role as a critical enabler of economic and supply chain resilience in the face of mounting global challenges.

2 THEORETICAL FRAMEWORK AND HYPOTHESIS DEVELOPMENT

This study's theoretical foundation is based on the Technology-Organization-Environment (TOE) framework and the Resource-Based View (RBV) theory. The TOE framework, created by (R. T. de Oliveira *et al.*, 2023), offers a thorough perspective on the determinants affecting the adoption of technical advancements. The adoption of new technologies, such as 'I 4.0 , is influenced by technical elements (e.g., perceived advantages, compatibility), organisational variables (e.g., company size, resources, preparedness), and environmental factors (e.g., competitive pressure, regulatory support). This approach is especially pertinent for comprehending the adoption of 'I 4.0 technologies inside Bangladesh's manufacturing sector, where technical and organisational preparedness, together with external influences, are crucial factors (Abdurrahman *et al.*, 2024). The RBV hypothesis enhances the Technology-Organization-Environment framework by emphasising the intrinsic capabilities of organisations. As per the RBV, organisations that have valuable, unique, inimitable, and non-substitutable resources may attain a competitive advantage (Majumdar *et al.*, 2021). Within the framework of 'I 4.0 , these resources include technical infrastructure, human capital, and organisational expertise that facilitate the successful application and integration of modern digital technologies. Utilising these resources, companies may augment their SCP via enhanced efficiency, innovation, and visibility (Ferreira *et al.*, 2022). The amalgamation of these two theoretical frameworks offers a comprehensive understanding of the determinants affecting 'I 4.0 adoption and its influence on SCP. The TOE framework identifies contextual elements influencing adoption, while RBV emphasises the strategic significance of organisational skills in using 'I 4.0 technology to enhance SCP. This integrated methodology facilitates a comprehensive knowledge of the interplay between technical, organisational, and environmental elements that affect the digital transformation of supply chains within the Bangladeshi manufacturing industry. Therefore, this study examines 'I 4.0 adoption level (I4AL), digital supply chain integration (DSCI), supply chain innovation (SCI), supply chain visibility (SCV), and supply chain performance (SCP) as interconnected constructs to explore their relationships and the overall impact of 'I 4.0 on the MS in Bangladesh.

The use of 'I 4.0 technology enables DSCI, characterised by uninterrupted data interchange and collaboration across supply chain participants. Digital integration facilitates instantaneous information exchange, optimises decision-making processes, and augments cooperation across the supply chain (Bag *et al.*, 2020). Recent studies indicate that the implementation of 'I 4.0 technologies, including IoT and cloud computing, markedly enhances digital supply chain integration by facilitating connectivity and interoperability among various supply chain entities (Núñez-Merino *et al.*, 2020).

H1: Industry 4.0 Adoption Level (I4AL) positively influences Digital Supply Chain Integration (DSCI).

'I 4.0 technologies are pivotal in advancing SCI by facilitating the creation and implementation of novel processes, goods, and services inside the supply chain. Innovations like smart manufacturing and predictive analytics enable companies to enhance production processes and adapt swiftly to market fluctuations (Szalavetz, 2019). Studies indicate that companies using 'I 4.0 technology are more inclined to embrace innovative practices, leading to improved operational capabilities and competitive advantage (Javaid, Haleem, Singh, & Suman, 2022).

H2a: Industry 4.0 Adoption Level (I4AL) positively influences Supply Chain Innovation (SCI).

The deployment of 'I 4.0 improves SCV by facilitating real-time access to essential data across the whole supply chain network. Technologies like IoT, RFID, and blockchain enable companies to monitor and track goods, inventories, and shipments in real time, hence enhancing transparency and traceability (Mubarak *et al.*, 2021)(Javaid, Haleem, Singh, Suman, *et al.*, 2022). Recent studies indicate that expanded supply chain visibility using 'I 4.0 technology results in superior demand forecasting, reduced lead times, and improved risk management (Helo & Shamsuzzoha, 2020)).

H2b: Industry 4.0 Adoption Level (I4AL) positively influences Supply Chain Visibility (SCV).

SCI profoundly influences SCP by incorporating novel technology and procedures that improve efficiency, responsiveness, and flexibility (Sunny *et al.*, 2020). Innovations like automated warehouses and sophisticated data analytics allow companies to optimise operations, save expenses, and enhance service quality. Research indicates that companies that engage in supply chain innovation often get superior performance results, such as enhanced delivery precision and increased customer satisfaction (Bag *et al.*, 2020; Spieske & Birkel, 2021).

H3: Supply Chain Innovation (SCI) positively influences Supply Chain Performance (SCP).

SCV is essential for attaining superior SCP, as it allows companies to proactively mitigate risks, optimise inventory levels, and improve cooperation with partners (Chowdhury *et al.*, 2019; Hong *et al.*, 2019). Augmented visibility reduces ambiguity and facilitates more precise planning and decision-making, resulting in enhanced operational performance. Recent studies indicate that companies with enhanced supply chain visibility often achieve superior performance regarding cost efficiency, delivery dependability, and overall agility (Baah *et al.*, 2022; Sheel & Nath, 2019).

H4: Supply Chain Visibility (SCV) positively influences Supply Chain Performance (SCP).

DSCI is a crucial factor in enhancing SCP by facilitating uninterrupted communication, coordination, and cooperation across supply chain stakeholders. Integrated digital systems enable companies to exchange real-time data, coordinate operations, and swiftly adapt to fluctuations in demand or supply situations (Enrique *et al.*, 2022). Research indicates that companies exhibiting elevated degrees of digital supply chain integration often attain superior performance results, including diminished lead times, decreased costs, and enhanced service quality (Choudhury *et al.*, 2021; Shukor *et al.*, 2021).

H5: Digital Supply Chain Integration (DSCI) positively influences Supply Chain Performance (SCP).

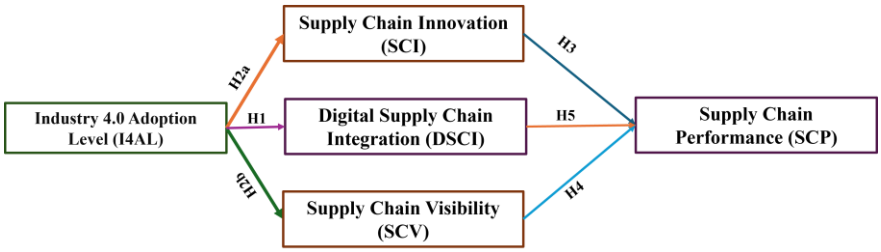

Figure 1 - Research Framework

3 MATERIALS AND METHOD

The study adopted a quantitative approach to examine the effects of 'I 4.0 implementation on SCP within Bangladesh's industrial sector. The research used primary data gathered via a standardized questionnaire administered to workers at manufacturing companies.

This study employed a quantitative approach to investigate the effects of Industry 4.0 (I4.0) implementation on supply chain performance (SCP) within Bangladesh's industrial sector. Primary data was collected through a structured questionnaire administered to employees directly involved in supply chain management, such as supply chain managers, operations and logistics executives, and IT professionals who have expertise in supply chain functions. Respondents were selected based on their job roles to ensure familiarity with I4.0 concepts.

A convenience sampling method was employed, allowing for efficient access to participants. A total of 570 questionnaires were distributed, yielding 379 responses. After excluding incomplete and erroneous entries, 350 valid responses were retained, providing a robust sample size for analysis. Data collection spanned six months, ensuring adequate representation across diverse job roles within the manufacturing sector.

The questionnaire was designed using validated scales from prior studies, measuring constructs such as digital supply chain integration (DSCI), supply chain innovation (SCI), and supply chain visibility (SCV). A 5-point Likert scale was used to capture responses, enabling detailed data collection. To ensure the questionnaire's clarity and relevance, it underwent pre-testing with field

experts, and refinements were made based on their feedback. Content and construct validity were confirmed by aligning the items with theoretical constructs from prior research.

Data analysis was conducted using Partial Least Squares Structural Equation Modeling (PLS-SEM) with the SmartPLS software. PLS-SEM was chosen for its capability to handle complex predictive models, non-normal data distributions, and small to medium sample sizes effectively (Hair *et al.*, 2019). Unlike covariance-based SEM (CB-SEM) tools like AMOS and LISREL, PLS-SEM is particularly suited for exploratory research as it provides a comprehensive analysis of both measurement models (validity and reliability) and structural models (hypothesis testing). Additionally, its visual representation of relationships facilitates better interpretation of results.

The reliability of the measurement scales was assessed using Cronbach's alpha, with all constructs demonstrating values above the commonly accepted threshold of 0.70 (Emon *et al.*, 2024; Hair Jr *et al.*, 2020; Izah *et al.*, 2023). This indicates a high level of internal consistency, underscoring the robustness of the scales and supporting the validity of the study's findings. The focus on Bangladesh's manufacturing sector was motivated by the sector's rapid progress toward digital transformation and adoption of I4.0 technologies. This context offers a relevant and dynamic environment to explore the interplay between I4.0 adoption and SCP.

Table 1 - Reliability of the Measurements

Constructs	Items	Cronbach's alpha
Industry 4.0 Adoption Level (I4AL)	8	0.93
Digital Supply Chain Integration (DSCI)	3	0.88
Supply Chain Innovation (SCI)	5	0.85
Supply Chain Visibility (SCV)	3	0.83
Supply Chain Performance (SCP)	4	0.91

4 RESULTS

Table 2 delineates the demographic characteristics of the 350 respondents who engaged in the survey. The data reveals that male participants constitute 60.86% of the total, and female respondents represent 39.14%. The age distribution shows that most respondents fall within the 31–40 years (49.14%) and 41–50 years (44.57%) age brackets, indicating a mid-career workforce. This suggests a balance between experienced professionals and relatively younger employees, highlighting the sector's reliance on both seasoned expertise and fresh perspectives. A substantial percentage of respondents with a Master's degree (47.71%), closely followed by those with a Bachelor's degree (44.00%). This elevated educational achievement is crucial for comprehending and using sophisticated 'I 4.0 technologies, which want specialist knowledge and abilities. A minority of respondents have a Diploma (5.43%) or other credentials (2.86%), suggesting that further education is a prevalent need for employment in the manufacturing industry. The respondents' current job status indicates that a significant majority are mid-level employees (72.57%), presumably engaged in managing supply chain operations and integrating new technology. Senior-level personnel comprise 22.57%, indicating their strategic supervision function within the company. Entry-level workers include just 4.86%, which corresponds with the sample's emphasis on persons with substantial job experience. The statistics on organization type indicates that a significant majority of respondents (93.14%) are engaged in private sector firms, whilst just 6.86% are employed in the public sector.. The distribution of work experience is extensive, with the majority of respondents (53.43%) possessing 4–6 years of experience. This cohort, along with those with 7–10 years of experience (26.00%), presumably comprises persons who are proficient in the operational and strategic requirements of the manufacturing industry. Individuals with over 10 years of experience constitute 7.71%, whilst individuals with less than 1 year and 1–3 years of experience account for lesser proportions of the sample at 2.00% and 10.86%, respectively. The distribution indicates that the sample mostly comprises seasoned experts with an extensive grasp of supply chain dynamics, enabling them to provide informed perspectives on the implementation of 'I 4.0 technologies.

Table 2 - Demographic Profile of The Respondents

Variable	N	(%)
Gender		
Male	213	60.86%
Female	137	39.14%
Age		

20-30 Years	9	2.57%
31–40 Years	172	49.14%
41–50 Years	156	44.57%
50 Years and Above	13	3.71%
Educational Qualification		
Bachelor's Degree	154	44.00%
Master's Degree	167	47.71%
Diploma	19	5.43%
Others	10	2.86%
Current Employment Status		
Entry-level employee	17	4.86%
Mid-level employee	254	72.57%
Senior-level employee	79	22.57%
Organization Type		
Public	24	6.86%
Private	326	93.14%
Years of Work Experience		
Less than 1 year	7	2.00%
1–3 years	38	10.86%
4–6 years	187	53.43%
7–10 years	91	26.00%
More than 10 years	27	7.71%
Total	350	100.00%

Table 3 displays the measurement model, demonstrating the reliability and validity of the constructs used in the research, evaluated by factor loadings, average variance extracted (AVE), and composite reliability (CR). The model's assessment demonstrates an adequate degree of reliability and convergent validity across all dimensions, which is crucial for affirming the robustness and trustworthiness of the study outcomes (Hair *et al.*, 2020). The construct "I4AL" has eight components with factor loadings between 0.72 and 0.90. The elevated factor loadings exceed the suggested threshold of 0.70, indicating that each item sufficiently embodies the construct (Fornell & Larcker, 1981). The AVE for this construct is 0.67, above the allowed minimum of 0.50, indicating that over half of the variation in the items is accounted for by the construct. The CR of 0.93 reinforces the internal consistency of the concept, above the established threshold of 0.70 (Hair *et al.*, 2020). For the construct "DSCI," all three items have factor loadings above 0.87, with an AVE of 0.81 and a CR of 0.88. The elevated AVE value indicates robust convergent validity, indicating that the items together encapsulate the core of the concept (Fornell & Larcker, 1981). The CR value, above the threshold, validates the construct's dependability and internal consistency, hence endorsing its incorporation into the model. SCI is assessed by five items, with loadings between 0.72 and 0.86. The AVE for this construct is 0.62, indicating that a significant percentage of the variation is accounted for by the construct. A CR of 0.85 signifies a dependable and consistent assessment of supply chain innovation. This consistency is essential for analyzing the impact of innovation on SCP, as emphasized in prior study (Dubey *et al.*, 2021). The concept of " SCV" has three elements with factor loadings ranging from 0.80 to 0.91, an AVE of 0.75, and a CR of 0.83. The elevated loadings and AVE indicate that the construct is effectively assessed by its indicators, while the CR value corroborates its dependability. SCV is essential for the efficient management and performance of supply networks, especially within the framework of 'I 4.0 (Ahmed *et al.*, 2021). Finally, "SCP" is assessed using four items, with loadings ranging from 0.84 to 0.92. The AVE of 0.79 and the CR of 0.91 demonstrate that this construct is valid and dependable. Elevated AVE and CR values are crucial for confirming that the measurement model effectively represents the construct of SCP, which is fundamental to comprehending the entire influence of 'I 4.0 adoption on operational results. The measurement model has robust psychometric features, with all constructs satisfying the necessary requirements for convergent validity and reliability. This provides a robust basis for further structural analysis and hypothesis testing. The findings validate that the selected indicators accurately represent the relevant constructs, allowing a comprehensive examination of the correlation between 'I 4.0 adoption and SCP in Bangladesh's MS (Fornell & Larcker, 1981; Hair *et al.*, 2020).

Table 3 - Measurement Model

Constructs	Items	Loading	AVE	CR
Industry 4.0 Adoption Level (I4AL)	I4AL1	0.79	0.67	0.93
	I4AL2	0.74		
	I4AL3	0.80		
	I4AL4	0.72		
	I4AL5	0.88		
	I4AL6	0.85		
	I4AL7	0.84		
	I4AL8	0.90		
Digital Supply Chain Integration (DSCI)	DSCI1	0.91	0.81	0.88
	DSCI2	0.91		
	DSCI3	0.87		
Supply Chain Innovation (SCI)	SCI1	0.72	0.62	0.85
	SCI2	0.76		
	SCI3	0.82		
	SCI4	0.86		
	SCI5	0.76		
Supply Chain Visibility (SCV)	SCV1	0.91	0.75	0.83
	SCV2	0.87		
	SCV3	0.80		
Supply Chain Performance (SCP)	SCP1	0.84	0.79	0.91
	SCP2	0.92		
	SCP3	0.87		
	SCP4	0.92		

Table 4 illustrates the discriminant validity of the notions according to the Fornell-Larcker criteria. Per this criteria, the √AVE for each construct (shown by the diagonal values) must exceed its association with every other construct inside the model (Fornell & Larcker, 1981). This method is essential for evaluating the distinctiveness of the constructs, hence guaranteeing the model's validity and the reliability of the results (Hair *et al.*, 2019). The √AVE for "DSCI" is 0.90, exceeding its associations with "I4AL" (0.49), "SCI" (0.75), "SCP" (0.70), and "SCV" (0.70). This indicates that DSCI is a unique construct, since it exhibits more variation with its indicators than with other constructs. This uniqueness is essential within the framework of 'I 4.0 , where digital integration is seen as an independent factor affecting SCP. The √AVE for the "I4AL" construct is 0.82, exceeding its correlations with other constructs: DSCI (0.49), SCI (0.65), SCP (0.56), and SCV (0.54). This verifies that the I4AL construct is distinct and clearly distinguishable from other constructions. I4AL signifies the degree of advanced technology adoption in the supply chain, making its distinct distinction essential for comprehending its specific influence on supply chain results. The construct "SCI" has a square root of AVE value of 0.79, exceeding its associations with DSCI (0.75), I4AL (0.65), SCP (0.73), and SCV (0.75). This signifies that the SCI framework is unique, confirming that the new methods and technology used in the supply chain are distinctly enhancing performance benefits. The √AVE for "SCP" is 0.89, surpassing its associations with DSCI (0.70), I4AL (0.56), SCI (0.73), and SCV (0.81). This indicates that SCP, as a concept, is unique and that the metrics used to assess supply chain effectiveness reflect its specific characteristics. This is important since SCP is the primary outcome variable in this research, indicating the overall efficacy and efficiency of supply chain operations affected by the adoption of 'I 4.0 . Finally, "SCV" has a √AVE of 0.86, surpassing its correlations with DSCI (0.70), I4AL (0.54), SCI (0.75), and SCP (0.81). This substantiates SCV as an independent concept, emphasizing its function in delivering transparency and real-time data across the supply chain. The explicit differentiation of SCV is vital, since visibility is a critical element in addressing supply chain disruptions and improving coordination, particularly in intricate and digital settings. The Fornell-Larcker criteria verifies that each construct in the model has a greater AVE than its correlations with other constructs, hence proving sufficient discriminant validity. This guarantees that the constructs are conceptually differentiated and that the model offers a dependable framework for examining the effects of 'I 4.0 adoption on SCP within Bangladesh's industrial sector (Fornell & Larcker, 1981; Hair Jr *et al.*, 2020).

Table 4 - Fornell-Larcker criterion

Constructs	DSCI	I4AL	SCI	SCP	SCV
DSCI	0.90				
I4AL	0.49	0.82			
SCI	0.75	0.65	0.79		
SCP	0.70	0.56	0.73	0.89	
SCV	0.70	0.54	0.75	0.81	0.86

Table 5 displays the outcomes of the hypothesis testing conducted by structural equation modeling (SEM). The table indicates that all presented hypotheses have been accepted, shown by substantial T-statistics and P-values below 0.05. This offers substantial support for the theoretical model and the interrelations across constructs regarding 'I 4.0 adoption and its effect on SCP. Hypothesis 1 (H1) said that the level of 'I 4.0 adoption (I4AL) has a favorable effect on DSCI. The hypothesis was corroborated by a T-statistic of 9.34 and a P-value of 0.00, indicating a substantial positive correlation. Hypothesis 2a (H2a) posited a favorable correlation between I4AL and SCI. The findings provide robust evidence for this hypothesis, shown by a T-statistic of 14.73 and a P-value of 0.00. The use of modern technology promotes innovation in supply chains, allowing enterprises to create new processes, products, and business models to maintain competitiveness in a swiftly changing market. This is especially pertinent for industrial companies in Bangladesh aiming to use 'I 4.0 to improve their innovative capabilities. Hypothesis 2b (H2b), positing a positive correlation between I4AL and SCV, was affirmed with a T-statistic of 11.17 and a P-value of 0.00. This indicates that the use of 'I 4.0 technology markedly enhances visibility across the supply chain, including real-time tracking and monitoring functionalities. This increased visibility is essential for proactive decision-making and risk management. Hypothesis 3 (H3) investigated the correlation between SCI and SCP, yielding a T-statistic of 3.16 and a P-value of 0.00, so confirming the hypothesis. This signifies that improvements in the supply chain result in enhanced performance metrics, including efficiency, responsiveness, and customer satisfaction. Hypothesis 4 (H4) posited a beneficial effect of SCV on SCP. The hypothesis was validated with a T-statistic of 11.40 and a P-value of 0.00. This underscores that greater visibility substantially enhances overall SCP, facilitating better coordination, reduced lead times, and elevated service levels. Research has continually highlighted the essential importance of visibility in the management of intricate supply chains, especially in unpredictable contexts. Hypothesis 5 (H5) proposed that DSCI has a positive impact on SCP, which was corroborated by a T-statistic of 3.40 and a P-value of 0.00. This discovery highlights the significance of digital integration in attaining enhanced SCP. Digital supply chains exhibit enhanced agility and responsiveness, allowing companies to swiftly adjust to fluctuations in demand and supply circumstances. In the industrial sector of Bangladesh, this signifies that investment in digital technology is essential for sustaining competitiveness and improving performance. The hypothesis testing findings provide extensive empirical data corroborating the postulated links inside the theoretical model. The results indicate that the implementation of 'I 4.0 substantially influences several facets of supply chain management, resulting in enhanced SCP. This underscores the need for manufacturing companies in Bangladesh to adopt digital transformation and incorporate modern technologies into their supply chains to succeed in a more digitized and competitive environment.

Table 5 - Hypothesis Testing

Hypothesis	Relationship	T statistics	P values	Decision
H1	I4AL -> DSCI	9.34	0.00	Accepted
H2a	I4AL -> SCI	14.73	0.00	Accepted
H2b	I4AL -> SCV	11.17	0.00	Accepted
H3	SCI -> SCP	3.16	0.00	Accepted
H4	SCV -> SCP	11.40	0.00	Accepted
H5	DSCI -> SCP	3.40	0.00	Accepted

Table 6 displays the R^2 and modified R^2 values for the constructs analyzed in the structural model. These numbers represent the extent of variation in the dependent variables accounted for by the independent variables in the model. The R^2 value for DSCI is 0.24, indicating that 24% of the variation in DSCI is attributable to the degree of 'I 4.0 adoption (I4AL). This indicates that whereas I4AL significantly influences the degree of digital integration, other variables may also affect this construct. The R^2 value for SCI is 0.42, indicating that 42% of the variation in SCI is explained by I4AL. This comparatively elevated figure indicates a robust correlation between the adoption of 'I 4.0 and

innovation in the supply chain. The R^2 score for SCP is 0.71, the highest ever. This signifies that 71% of the diversity in SCP can be elucidated by the collective influences of I4AL, SCI, DSCI, and SCV. This significant value underscores the essential impact these elements have in enhancing SCP. Finally, the R^2 value for SCV is 0.29, indicating that 29% of the variation in SCV is elucidated by I4AL. Although this value is inferior to that of SCP and SCI, it nonetheless indicates a significant correlation, implying that while 'I 4.0 technologies are essential for enhancing visibility, other factors such as collaboration and data-sharing practices are also vital.

Table 6 - R^2 and R^2 Adjusted

Constructs	R^2	R^2 adjusted
DSCI	0.24	0.24
SCI	0.42	0.42
SCP	0.71	0.71
SCV	0.29	0.29

Figure 2 illustrates the outcomes of the SEM analysis using the Partial Least Squares (PLS) method, emphasizing the path coefficients and interrelations among the constructs in the research. This model demonstrates the effect of I4AL on critical supply chain elements—SCI, DSCI, and SCV—and their subsequent impact on overall SCP. The path coefficient from I4AL to SCI is 0.65, indicating a significant positive correlation. Higher levels of 'I 4.0 adoption markedly improve enterprises' capacity to innovate in their supply chains by integrating sophisticated technologies and processes to optimize operations and secure competitive advantages. The R^2 value of 0.42 for SCI indicates that 42% of the variation in supply chain innovation is accounted for by the use of 'I 4.0 technology, indicating a significant impact. The correlation between I4AL and DSCI has a path coefficient of 0.49, indicating a substantial positive impact. This relationship underscores the significance of implementing 'I 4.0 technologies, including IoT and cloud computing, to facilitate seamless digital integration throughout the supply chain, thereby improving data exchange, coordination, and collaboration among supply chain partners. The R^2 value of 0.24 for DSCI indicates that 24% of its variation is accounted for by the adoption of 'I 4.0 , which is modest but statistically significant. The path coefficient between I4AL and SCV is 0.54, indicating a significant positive influence. The adoption of 'I 4.0 technologies enhances supply chain visibility by facilitating real-time tracking and monitoring of goods and information throughout the supply chain, consequently diminishing uncertainties and augmenting decision-making capabilities. The R^2 value for SCV is 0.29, indicating that 29% of the variation in supply chain visibility is attributable to 'I 4.0 adoption. The model demonstrates the influence of various intermediate constructions on SCP. The path coefficient from SCI to SCP is 0.18, indicating a modest positive correlation. This indicates that supply chain innovation, propelled by 'I 4.0 , enhances SCP by promoting the creation of novel solutions and procedures. The route coefficient from DSCI to SCP is 0.18, indicating a comparable degree of positive influence, which supports the notion that enhanced digital integration results in greater supply chain efficiency and effectiveness. The most robust association in the model is between SCV and SCP, characterized by a path coefficient of 0.55. This discovery emphasizes the essential importance of supply chain visibility in improving performance metrics, including operational efficiency, responsiveness, and customer satisfaction. Enhanced visibility enables companies to proactively address supply chain problems, optimize inventory management, and enhance overall coordination. The model accounts for 71% of the variance in SCP (R^2 = 0.71), signifying that the synergistic effects of 'I 4.0 adoption, supply chain innovation, digital integration, and visibility substantially enhance the performance of MS supply chains in Bangladesh. This extensive model highlights the need of adopting 'I 4.0 technologies to enhance supply chain efficiency, innovation, and resilience within a changing global market.

Figure 2 - Structural Equation Modelling and Path Coefficient (PLS SEM Approach)

5 DISCUSSION

This research examines the effects of 'I 4.0 implementation on SCP within Bangladesh's industrial sector. A quantitative methodology was adopted to gather data from 350 respondents using a structured questionnaire, with Smart PLS utilized for statistical analysis. The results indicate that the implementation of 'I 4.0 markedly affects DSCI, SCI, and SCV, which subsequently influence overall SCP.

Findings reveal that I4.0 adoption significantly enhances DSCI (T-statistic: 9.34, $p < 0.001$). This aligns with de Oliveira & Handfield, (2019), who emphasized that digital integration reduces fragmentation and enhances real-time decision-making. By seamlessly linking different supply chain elements, DSCI minimizes operational inefficiencies and improves coordination, ultimately contributing to superior SCP.

I4.0 adoption also strongly influences SCI (T-statistic: 14.73, $p < 0.001$), highlighting the role of emerging technologies in fostering innovation. This finding is consistent with the Dynamic Capabilities Theory, which underscores technological adaptation as a driver of competitive advantage (Mikalef & Pateli, 2017). The integration of technologies such as IoT, AI, and robotics in manufacturing enhances the sector's capability to innovate, adapt to dynamic market demands, and create value.

Enhanced visibility through I4.0 technologies significantly impacts SCV (T-statistic: 11.17, $p < 0.001$). Increased visibility provides firms with actionable insights for better risk management, demand forecasting, and real-time tracking, as supported by Emon & Khan, (2024). These capabilities are particularly vital in the Bangladeshi MS, where supply chain complexity often leads to inefficiencies.

The mediating roles of DSCI, SCI, and SCV in improving SCP were validated, indicating that technology-driven integration, innovation, and visibility collectively drive operational excellence and sustainability. These findings corroborate the Resource-Based View (RBV), which posits that leveraging organizational resources such as innovation and visibility enhances competitive advantage (Butt, 2020; Ishfaq *et al.*, 2022; Zekhnini *et al.*, 2021).

This research enhances the existing literature in several ways. Firstly, it offers empirical evidence on the advantages of I4.0 adoption in the context of a developing economy like Bangladesh, which has been underexplored in previous studies (Debnath *et al.*, 2023; Saha *et al.*, 2022). By integrating the Technological-Organizational-Environmental (TOE) framework with RBV, this study provides a holistic perspective on the antecedents and outcomes of I4.0 adoption. While the TOE framework identifies the factors influencing technology adoption, RBV explains how these technologies create value by enhancing organizational resources such as DSCI, SCI, and SCV (AL-Khatib *et al.*, 2024; Lutfi *et al.*, 2023; Reza *et al.*, 2024). Moreover, this study contributes to understanding the mediating effects of DSCI, SCI, and SCV on SCP, offering a more comprehensive framework for assessing the implications of digital transformation in supply chains. This integration provides a valuable foundation for future research to explore other mediating and moderating variables, such as organizational culture and external environmental factors, in understanding digital transformation.

The findings offer actionable insights for practitioners and policymakers in Bangladesh's MS. Firms aiming to enhance SCP should prioritize I4.0 adoption to achieve superior integration, promote innovation, and improve visibility across the supply chain. The substantial impact of these mediating variables on SCP highlights the need for complementary investments in training, process

reengineering, and infrastructure development to maximize the benefits of digital transformation (Asamoah *et al.*, 2021; Jimenez-Jimenez *et al.*, 2019; Zeng & Lu, 2021). Policymakers should advocate for incentives and policies that support I4.0 technology adoption, thereby improving the global competitiveness of Bangladeshi enterprises. These initiatives should focus on reducing barriers to adoption, such as high implementation costs and the lack of skilled professionals, to ensure the broad diffusion of these technologies.

6 CONCLUSION

This study examined the impact of Industry 4.0 (I4.0) adoption on supply chain performance (SCP) within Bangladesh's industrial sector, addressing a significant gap in the existing literature on digital transformation in emerging economies. While the global emphasis on integrating advanced technologies into supply chains continues to grow, empirical evidence from developing nations like Bangladesh remains limited. This research sought to fill that gap by exploring the relationships among I4.0 adoption, digital supply chain integration (DSCI), supply chain innovation (SCI), supply chain visibility (SCV), and overall SCP. The findings reveal that I4.0 adoption significantly enhances DSCI, SCI, and SCV, which in turn drive notable improvements in SCP. The study highlights that I4.0 technologies facilitate effective data exchange, real-time monitoring, and enhanced decision-making capabilities, all of which are critical for achieving operational excellence. Additionally, SCI and SCV emerged as essential mediators, emphasizing that simply adopting advanced technologies is insufficient. Organizations must foster an innovative culture and improve transparency across supply chains to fully leverage the benefits of digital transformation. These findings carry important implications for both practitioners and policymakers. For manufacturing firms in Bangladesh and other emerging economies, I4.0 adoption is vital to maintaining competitiveness in an increasingly dynamic global market. The positive correlation between I4.0 adoption and SCP underscores the potential of digital transformation to meet market demands, reduce costs, and enhance customer satisfaction. Policymakers, on the other hand, can use these insights to devise targeted strategies that support technological advancements and strengthen the global competitiveness of local enterprises.

This research bridges a critical gap in understanding the impact of I4.0 adoption on SCP in a developing country context. By integrating existing theoretical frameworks and presenting empirical evidence from Bangladesh, it contributes significantly to academic research and practical applications. Future research should explore additional mediators and moderators, such as organizational culture and external environmental factors, to provide a more nuanced understanding of digital transformation in supply chains. Longitudinal studies could also provide deeper insights into the long-term effects of I4.0 implementation on supply chain efficiency and organizational sustainability. These avenues for future exploration will contribute to a more comprehensive understanding of digital transformation in supply chain management and offer nuanced recommendations for stakeholders in emerging economies. Moreover, emerging concepts like Industry 5.0, which emphasize human-centric and collaborative systems, offer promising directions for further investigation.

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