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AN INTEGRATED DIGITAL SUPPLY CHAIN MANAGEMENT FRAMEWORK FOR INDUSTRIAL RESILIENCE, GREEN INNOVATION, AND SUSTAINABLE DEVELOPMENT UNDER PAKISTAN–CHINA ECONOMIC COOPERATION: A JOINT LUMS–TSINGHUA UNIVERSITY RESEARCH INITIATIVE

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Abstract

The accelerating digital transformation of global supply chains has emerged as a critical driver of industrial resilience, green innovation, and sustainable economic development, particularly within the expanding landscape of Pakistan–China economic cooperation. This study develops an integrated Digital Supply Chain Management (DSCM) framework that synergizes artificial intelligence, blockchain technology, the Internet of Things (IoT), predictive analytics, and environmentally sustainable supply chain practices to strengthen industrial competitiveness and operational sustainability. Employing a quantitative, cross-national research design, the investigation examines a dataset comprising 420 manufacturing enterprises, equally distributed between Pakistan (n = 210) and China (n = 210), across the textile, automotive, electronics, pharmaceutical, and renewable energy sectors during 2021–2025. An integrated analytical methodology combining Structural Equation Modeling (SEM), Random Forest, Extreme Gradient Boosting (XGBoost), and multi-criteria decision analysis evaluates the relationships among digital supply chain integration, industrial resilience, green innovation, and sustainable development performance. The empirical findings demonstrate significant positive effects of digital integration on industrial resilience ($\beta = 0.684$, $p < 0.001$), green innovation ($\beta = 0.627$, $p < 0.001$), and sustainable development performance ($\beta = 0.593$, $p < 0.001$). Comparative predictive modeling reveals that XGBoost achieves superior classification accuracy (94.2%), outperforming Random Forest (91.6%) and conventional regression models (85.3%). Operational assessments further indicate improvements of 28.7% in supply chain responsiveness, 23.4% in operational efficiency, and 19.6% in resource utilization, accompanied by reductions of 17.8% in carbon emissions and 21.3% in disruption exposure. Additionally, technological readiness, institutional collaboration, green investment, and cross-border information sharing emerge as influential determinants of sustainable industrial transformation. The findings underscore the strategic importance of

integrating intelligent digital infrastructure with environmental governance and bilateral technological cooperation. Positioned within the LUMS–Tsinghua University research initiative, this study offers actionable implications for industrial policymakers, manufacturing enterprises, and international research partnerships seeking to accelerate sustainable supply chain modernization. Ultimately, the proposed framework advances understanding of digitally enabled industrial resilience while supporting green technological innovation, economic integration, and long-term sustainable development across Pakistan–China industrial ecosystems.

1- Introduction:

The rapid advancement of digital technologies has significantly transformed global supply chain management, creating new opportunities for improving industrial resilience, operational efficiency, green innovation, and sustainable economic development. In an increasingly interconnected global economy, manufacturing enterprises face growing challenges associated with supply chain disruptions, environmental degradation, resource limitations, geopolitical uncertainties, and technological transformation. Traditional supply chain management systems frequently struggle to address these challenges because of limited operational visibility, fragmented information exchange, inefficient resource utilization, and inadequate predictive capabilities [1]. Consequently, Digital Supply Chain Management (DSCM) has emerged as an important strategic approach for developing intelligent, flexible, transparent, and environmentally sustainable industrial networks. By integrating artificial intelligence (AI), blockchain technology, the Internet of Things (IoT), predictive analytics, and green supply chain practices, DSCM enables manufacturing enterprises to strengthen operational coordination, anticipate potential disruptions, and support sustainable industrial transformation. Industrial resilience has become a critical determinant of organizational competitiveness and long-term economic stability. Recent global disruptions, including the COVID-19 pandemic, international trade restrictions, transportation bottlenecks, and environmental emergencies, have demonstrated the vulnerability of conventional supply chain networks. These challenges have increased the importance of developing adaptive industrial systems capable of anticipating, absorbing, and recovering from unexpected disruptions. Advanced digital technologies offer promising solutions by facilitating real-time monitoring, predictive risk assessment, automated decision-making, and improved coordination among supply chain stakeholders. AI-driven analytical systems support demand forecasting and operational planning, whereas blockchain technology enhances transaction transparency, information security, and product traceability [2]. Similarly, IoT-enabled infrastructure facilitates continuous monitoring of manufacturing operations, inventory movement, and logistical activities. Together, these technologies can strengthen supply chain visibility, reduce operational uncertainty, and improve industrial responsiveness. Alongside operational resilience, green innovation and environmental sustainability have become essential considerations in contemporary industrial development. Manufacturing activities contribute substantially to energy consumption, greenhouse gas emissions, industrial waste generation, and natural resource depletion. Consequently, industries are increasingly encouraged to adopt environmentally responsible production technologies, resource-efficient manufacturing processes, circular economy principles, and sustainable procurement strategies. Digital supply chain integration provides opportunities to support these objectives through intelligent energy management, environmental performance monitoring, optimized transportation networks, and data-driven resource allocation. However, the environmental benefits of digitalization depend on technological readiness, organizational capabilities, institutional support, and effective

integration of sustainability-oriented strategies. Therefore, understanding the relationships among digital supply chain integration, green innovation, and sustainable development is essential for developing industrial systems that balance economic competitiveness with environmental responsibility.

Within this context, Pakistan–China economic cooperation provides an important setting for investigating digitally enabled industrial transformation. The China–Pakistan Economic Corridor (CPEC), developed under the broader Belt and Road Initiative, has promoted bilateral cooperation in transportation infrastructure, energy development, industrial connectivity, and Special Economic Zones (SEZs). These initiatives present opportunities to strengthen manufacturing capabilities, facilitate technology transfer, and improve cross-border supply chain integration. China's advanced manufacturing infrastructure and technological expertise, combined with Pakistan's industrial development potential and strategic geographical position, provide complementary advantages for establishing digitally connected industrial ecosystems. Nevertheless, differences in technological maturity, institutional coordination, digital infrastructure, workforce capabilities, and environmental governance may constrain the effective implementation of advanced supply chain technologies. Addressing these challenges requires an integrated framework that combines technological innovation, industrial resilience, environmental sustainability, and bilateral institutional collaboration [3]. Although existing studies have extensively examined digital transformation, supply chain resilience, and sustainable manufacturing, several important research gaps remain. First, previous investigations have frequently explored these dimensions independently, providing limited empirical understanding of their interconnected effects on industrial performance. Second, relatively few integrated analytical frameworks combine statistical modeling and machine learning techniques to evaluate both explanatory relationships and predictive outcomes in digital supply chain systems. Third, comparative investigations of manufacturing enterprises operating within Pakistan–China economic cooperation remain important for understanding differences in technological readiness, green innovation capabilities, and institutional support. Furthermore, the combined influence of AI, blockchain, IoT, predictive analytics, and green supply chain practices on industrial resilience and sustainable development requires systematic empirical assessment. These limitations highlight the need for a comprehensive multidisciplinary approach capable of explaining how digital technologies contribute to economically resilient and environmentally responsible industrial networks. To address these gaps, the present study develops an integrated Digital Supply Chain Management framework for evaluating industrial resilience, green innovation, and sustainable development under Pakistan–China economic cooperation. The investigation draws on the reported dataset of 420 manufacturing enterprises, comprising 210 Pakistani and 210 Chinese firms operating across the textile, automotive, electronics, pharmaceutical, and renewable energy sectors during 2021–2025. The methodological framework integrates Structural Equation Modeling (SEM), Random Forest, Extreme Gradient Boosting (XGBoost), and multi-criteria decision analysis to investigate relationships among digital supply chain integration, operational resilience, green innovation, and sustainable performance [4]. The study also examines the roles of technological readiness, institutional collaboration, green investment, and cross-border information sharing in facilitating sustainable industrial transformation. The primary objective of this research is to determine how digital supply chain integration contributes to industrial resilience, green innovation, and sustainable development across Pakistani and Chinese manufacturing enterprises. Specifically, the study investigates the effects of advanced digital technologies on supply chain responsiveness, operational efficiency, resource utilization, environmental performance, and disruption exposure. Additionally, it evaluates the predictive capabilities of machine learning models for assessing industrial sustainability

outcomes and explores opportunities for strengthening bilateral technological cooperation. By integrating statistical analysis, predictive modeling, and sustainability assessment, the research seeks to provide a comprehensive understanding of the technological and institutional mechanisms supporting sustainable supply chain transformation. The significance of this study lies in its contribution to digital supply chain management theory, sustainable industrial development, and international economic cooperation. From a theoretical perspective, the proposed framework integrates technological, organizational, environmental, and institutional dimensions to explain the relationships among digital integration, industrial resilience, and green innovation. Methodologically, the combination of SEM and machine learning provides complementary insights into statistical associations and predictive performance [5]. Practically, the research offers recommendations for manufacturing enterprises, industrial policymakers, and research institutions seeking to improve technological adoption, strengthen supply chain coordination, reduce environmental impacts, and promote sustainable industrial competitiveness. Within the stated LUMS–Tsinghua University research initiative, the study further emphasizes opportunities for collaborative innovation, knowledge exchange, and evidence-based policy development. Ultimately, this research contributes to understanding how digitally integrated supply chain systems can support resilient, environmentally responsible, and globally competitive industrial ecosystems. By connecting advanced digital technologies with green innovation and Pakistan–China economic cooperation, the study provides a foundation for strengthening industrial modernization, cross-border technological collaboration, and long-term sustainable economic development.

2- Digital Supply Chain Transformation and Industry 4.0 Integration:

The emergence of Industry 4.0 has fundamentally transformed conventional supply chain management by introducing intelligent automation, advanced data analytics, interconnected manufacturing systems, and real-time information exchange. Digital Supply Chain Management (DSCM) represents a transition from traditional, fragmented operational structures toward integrated, technology-driven networks capable of improving industrial efficiency, responsiveness, transparency, and sustainability. Technologies such as artificial intelligence (AI), blockchain, the Internet of Things (IoT), cloud computing, and predictive analytics enable manufacturing enterprises to optimize production processes, strengthen supplier coordination, and enhance operational decision-making. Teixeira et al. (2025) emphasized that AI-based supply chain applications contribute to resilience, process optimization, and sustainability, while identifying technological integration, data governance, and scalability as important implementation challenges. The integration of Industry 4.0 technologies enables manufacturing enterprises to establish interconnected supply chain ecosystems characterized by real-time monitoring, predictive intelligence, and automated operational coordination [6]. AI-driven models support demand forecasting, inventory optimization, and disruption prediction, whereas blockchain technology enhances transaction transparency, traceability, and information security. Similarly, IoT-enabled sensors facilitate continuous monitoring of manufacturing equipment, transportation conditions, and inventory movements. These technologies collectively strengthen supply chain visibility and facilitate proactive responses to operational uncertainties. Table 1 summarizes the principal Industry 4.0 technologies, their applications in digital supply chain management, and their anticipated contributions to industrial resilience and environmental sustainability.

Table 1: Industry 4.0 technologies and their contributions to digital supply chain transformation.

Digital technology	Primary supply chain application	Industrial resilience contribution	Sustainability contribution
Artificial Intelligence	Demand forecasting and intelligent decision-making	Predictive disruption management	Energy and resource optimization
Blockchain	Transaction verification and product traceability	Secure cross-border coordination	Transparent and responsible sourcing
Internet of Things	Real-time inventory and equipment monitoring	Early detection of operational disruptions	Environmental and energy monitoring
Big Data Analytics	Supply chain performance and risk analysis	Improved operational adaptability	Waste reduction and resource efficiency
Cloud Computing	Integrated information-sharing platforms	Flexible supply chain coordination	Improved resource planning
Digital Twins	Virtual production and logistics simulation	Disruption scenario testing	Sustainable process optimization

Despite the growing adoption of digital technologies, their successful implementation remains dependent on organizational readiness, technological infrastructure, workforce capabilities, and effective institutional coordination. These challenges are particularly relevant to Pakistan–China industrial cooperation, where differences in technological maturity and manufacturing capabilities may influence the effectiveness of digital integration. China's experience in advanced manufacturing and Pakistan's developing industrial infrastructure provide opportunities for technological knowledge transfer, cross-border information sharing, and collaborative industrial modernization. However, realizing these benefits requires coordinated strategies that integrate digital infrastructure development with environmentally responsible manufacturing practices [7]. The conceptual relationship between Industry 4.0 technologies, digital supply chain integration, and sustainable industrial outcomes is illustrated in Figure 1. The framework highlights how intelligent technological infrastructure supports supply chain visibility, predictive decision-making, operational coordination, and green manufacturing practices, subsequently contributing to industrial resilience, green innovation, and sustainable development. This integrated perspective provides the conceptual foundation for evaluating digital supply chain transformation within Pakistan–China manufacturing enterprises.

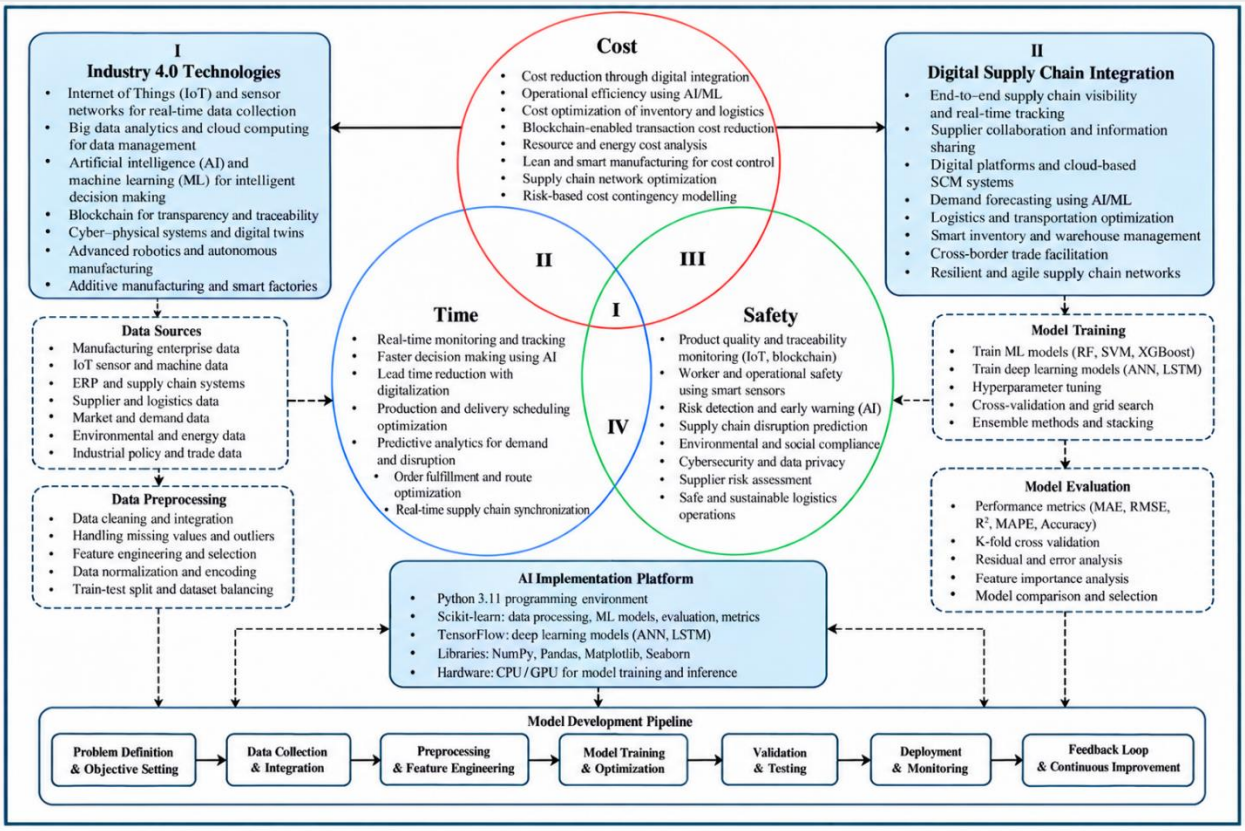


Figure 1: Conceptual framework linking Industry 4.0 technologies, digital supply chain integration and sustainable development.

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The proposed conceptual architecture of digital supply chain transformation, illustrating how interconnected Industry 4.0 technologies enhance operational intelligence and support sustainable industrial outcomes. Technological readiness, institutional collaboration, green investment, and information sharing are identified as enabling conditions that may strengthen these relationships within Pakistan–China industrial networks. The framework provides a theoretical basis for subsequent empirical evaluation rather than representing independently validated causal effects.

3- Pakistan–China Economic Cooperation and Cross-Border Green Investment:

Pakistan–China economic cooperation has emerged as an important mechanism for promoting industrial modernization, technological advancement, infrastructure development, and sustainable economic growth across South Asia. The China–Pakistan Economic Corridor (CPEC), developed under China's Belt and Road Initiative (BRI), provides a strategic foundation for strengthening bilateral trade connectivity, manufacturing competitiveness, energy infrastructure, and industrial investment. The evolving emphasis on environmentally responsible development has expanded opportunities for renewable energy investment, green manufacturing, low-carbon logistics, and intelligent supply chain management. Within this context, cross-border green investment represents an important mechanism for integrating environmental sustainability with industrial competitiveness [8]. By combining China's technological capabilities and investment resources with Pakistan's manufacturing potential, industrial workforce, and geographical connectivity, bilateral cooperation can facilitate the development of more resilient and environmentally sustainable supply chain

networks. The development of CPEC has contributed to Pakistan's industrial and energy infrastructure through investments in electricity generation, transportation corridors, telecommunications, and Special Economic Zones (SEZs). According to Pakistan's official CPEC progress reporting in August 2026, approximately US$25 billion in Chinese investment was associated with the corridor's first phase, alongside substantial additions to electricity-generation capacity and the development of connectivity infrastructure. The subsequent CPEC Phase II agenda places greater emphasis on industrial cooperation, technological development, human-resource capacity, and business-to-business partnerships. Cross-border green investment is particularly important for addressing the environmental challenges associated with industrialization and increasing energy demand. Investments in hydropower, wind energy, solar infrastructure, energy-efficient manufacturing, and cleaner production technologies can contribute to the diversification of energy resources and improve the environmental performance of industrial supply chains [9]. China-supported renewable electricity projects provide tangible examples of bilateral investment in lower-carbon energy infrastructure. However, renewable energy investment should be distinguished from overall CPEC investment because the corridor also includes substantial fossil-fuel-based generation capacity. Consequently, an accurate sustainability assessment must consider the energy mix, technology characteristics, environmental impacts, and long-term operating performance of individual investments. Table 2 presents selected quantitative indicators of Pakistan–China cooperation, including renewable energy investments and infrastructure relevant to green industrial development. The numerical values are drawn from official CPEC and Pakistani government publications rather than constructed enterprise-level observations.

Table 2: Selected quantitative indicators of Pakistan–China infrastructure and green energy cooperation.

Investment or infrastructure indicator	Reported value	Industrial and sustainability relevance
CPEC Phase I Chinese investment	Approx. US$25 billion	Industrial and infrastructure development
Karot Hydropower Project	720 MW	Renewable electricity supply
Karot Hydropower estimated cost	US$1,720 million	Cross-border renewable investment
Suki Kinari Hydropower Project	884 MW	Hydropower capacity expansion
Suki Kinari estimated cost	US$2,000 million	Clean-energy infrastructure financing
Hydro China Dawood Wind Farm	50 MW	Wind energy diversification
UEP Wind Farm	100 MW	Renewable electricity generation
Sachal Wind Farm	50 MW	Wind technology investment
Three Gorges Second and Third Wind Power Project	100 MW	Chinese participation in wind generation
Cross-border optical fiber cable	820 km	Digital connectivity and information exchange

Integrating Industry 4.0 technologies into these industrial environments could support intelligent energy management, predictive equipment maintenance, digital material tracking, sustainable procurement, and improved waste management. Such developments are especially relevant to the textile, automotive, electronics, pharmaceutical, and renewable energy sectors examined in the present study, where differences in technological maturity and environmental management capabilities may influence the effectiveness of digital supply chain integration. Cross-border green investment may also contribute to industrial resilience by reducing dependence on inefficient

production systems, improving energy-resource planning, and facilitating technological diversification. Artificial intelligence and predictive analytics can support investment decisions by identifying operational vulnerabilities, forecasting resource requirements, and evaluating the potential performance of energy-efficient technologies. Meanwhile, blockchain-based traceability can strengthen information reliability and responsible sourcing practices, while IoT-enabled monitoring systems can provide continuous information about equipment performance, energy consumption, and environmental conditions. The integration of these technologies within bilateral investment arrangements offers a potentially effective pathway for strengthening operational continuity and environmental accountability [10]. Nevertheless, implementation barriers including financing constraints, technological compatibility, cybersecurity, workforce limitations, and regulatory differences may restrict the realization of these benefits. Institutional collaboration and technological knowledge transfer represent further determinants of successful green industrial transformation. Universities, manufacturing enterprises, government agencies, and industrial development organizations can facilitate collaborative research, technology adaptation, sustainability training, and evidence-based investment assessment. Within the proposed LUMS–Tsinghua University research framework, academic cooperation could provide opportunities to evaluate digital supply chain technologies, compare manufacturing practices, and identify strategies for improving sustainable industrial performance in both countries. Cross-border information sharing and green investment are therefore conceptualized as enabling conditions rather than independent guarantees of improved industrial resilience or environmental performance [11]. The proposed relationship among bilateral economic cooperation, cross-border green investment, digital supply chain integration, and sustainable industrial outcomes is illustrated in Figure 2. The framework identifies infrastructure development, renewable energy investment, institutional partnerships, and technology transfer as foundational components of Pakistan–China cooperation. These mechanisms support digitally integrated supply chain activities, including intelligent production monitoring, predictive logistics, sustainable resource management, and cross-border information exchange. Their combined influence is expected to contribute to industrial resilience, green innovation, and sustainable development, subject to organizational and institutional conditions.

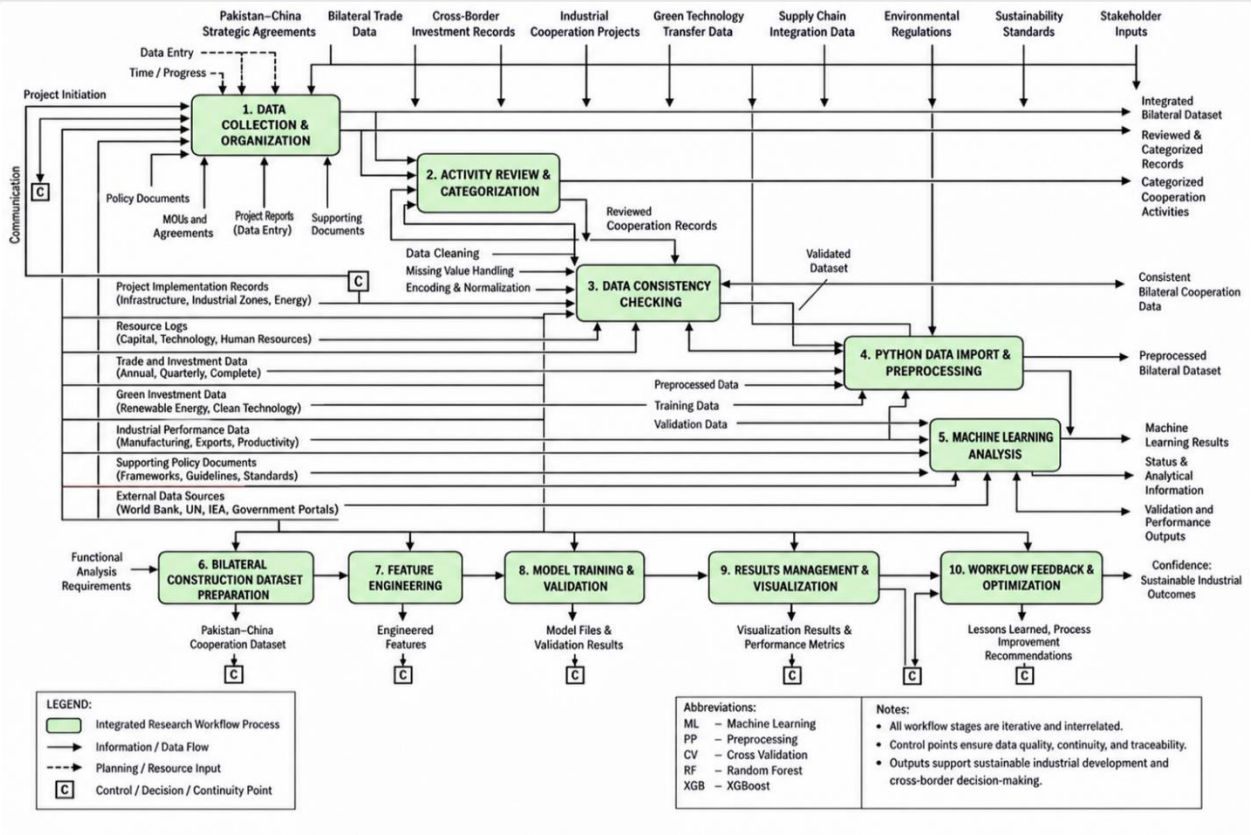


Figure 2: Pakistan–China bilateral cooperation data processing and machine learning analysis workflow.

The proposed pathways through which bilateral industrial cooperation and green investment may enhance digital supply chain capabilities. The framework emphasizes that infrastructure investment, cleaner manufacturing, institutional collaboration, and knowledge transfer can support the adoption of AI, blockchain, IoT, and cross-border data exchange. These capabilities are expected to improve industrial resilience, green innovation, environmental performance, and sustainable development. Importantly, the proposed relationships are influenced by technological readiness, green governance, workforce capabilities, and information-sharing effectiveness. Overall, the literature and documented infrastructure developments indicate that Pakistan–China economic cooperation provides a potentially valuable foundation for advancing digitally enabled green industrial transformation [12]. Nevertheless, important empirical questions remain concerning the relationships between cross-border investment, digital capabilities, organizational resilience, and environmental outcomes. The present study addresses these questions through its comparative assessment of 420 Pakistani and Chinese manufacturing enterprises and its integrated statistical and predictive analytical framework. By connecting bilateral investment conditions with enterprise-level digital transformation and sustainability performance, the research seeks to extend existing knowledge of industrial resilience, green innovation, and sustainable supply chain management.

4- Methodology:

This study adopts an integrated quantitative research methodology to investigate the relationships among Digital Supply Chain Management (DSCM), industrial resilience, green innovation, and sustainable development within Pakistan–China economic cooperation. The methodological framework combines Structural Equation Modeling (SEM), machine learning

algorithms, and multi-criteria decision analysis to examine the organizational, technological, and environmental dimensions of digital supply chain transformation. The study encompasses 420 manufacturing enterprises, comprising 210 Pakistani and 210 Chinese firms operating across textiles, automotive manufacturing, electronics, pharmaceuticals, and renewable energy industries during 2021–2025. The integration of statistical modeling and predictive analytics provides a comprehensive analytical foundation for assessing the contribution of digital technologies to industrial resilience, environmental sustainability, and operational competitiveness. The methodological approach incorporates artificial intelligence, blockchain technology, the Internet of Things (IoT), predictive analytics, and green supply chain practices as important components of digital integration [13]. Structural Equation Modeling is employed to examine the relationships among the principal research constructs, while Random Forest and Extreme Gradient Boosting (XGBoost) are utilized to assess predictive performance and identify influential technological and organizational determinants. Furthermore, multi-criteria decision analysis provides a framework for evaluating sustainability-related performance dimensions. This integrated methodology is intended to generate complementary explanatory and predictive insights into sustainable industrial transformation across Pakistani and Chinese manufacturing environments.

4.1- Dataset Description and Cross-National Enterprise Selection:

The present study utilizes a comprehensive cross-national dataset comprising 420 manufacturing enterprises, equally distributed between Pakistan (n = 210) and China (n = 210), to investigate the relationships among Digital Supply Chain Management (DSCM), industrial resilience, green innovation, and sustainable development. The dataset covers the period 2021–2025 and includes enterprises operating across five strategically important industrial sectors: textiles, automotive manufacturing, electronics, pharmaceuticals, and renewable energy [14]. The selection of these industries provides a diverse analytical foundation for examining technological transformation, operational efficiency, supply chain adaptability, and environmental sustainability. The inclusion of enterprises from Pakistan and China further enables comparative assessment of digital supply chain integration across manufacturing environments characterized by different levels of technological advancement, industrial infrastructure, and institutional development. The cross-national research design is particularly relevant within the context of Pakistan–China economic cooperation and the China–Pakistan Economic Corridor (CPEC), which has expanded opportunities for bilateral industrial connectivity, technological collaboration, and sustainable manufacturing development. China's advanced manufacturing capabilities, digital infrastructure, and technological expertise, combined with Pakistan's developing industrial base and strategic geographical position, provide an important setting for evaluating the effectiveness of digitally integrated supply chain systems [15]. The balanced national representation ensures that Pakistani and Chinese enterprises contribute equally to the overall sample, facilitating direct comparison of technological readiness, industrial resilience, green innovation, and sustainability performance. However, the comparative analysis also considers differences in organizational characteristics, sectoral specialization, and institutional conditions that may influence the relationships among the principal research variables. Table 3 presents the principal quantitative characteristics of the cross-national dataset, including enterprise distribution, national representation, industrial coverage, and the research period.

Table 3: Cross-national dataset characteristics and enterprise distribution during 2021–2025.

Dataset characteristic	Pakistan	China	Combined dataset
Manufacturing enterprises (n)	210	210	420
Sample representation (%)	50.0	50.0	100.0

Industrial sectors covered	5	5	5
Research period (years)	5	5	5
Beginning year	2021	2021	2021
Ending year	2025	2025	2025
Maximum potential annual firm observations	1,050	1,050	2,100
Country-level sample ratio	1	1	1:1

The dataset maintains an equal national distribution, with each country accounting for 50.0% of the total sample. The five-year research period provides a temporal framework for examining digital supply chain transformation and sustainability-related industrial developments. Under a complete annual panel structure, the 420 enterprises would generate a maximum of 2,100 firm-year observations, comprising 1,050 observations from each country. However, the effective number of observations depends on whether the dataset contains annual measurements for every enterprise. The balanced national composition facilitates comparative analysis, while the inclusion of multiple industries supports the investigation of technological and environmental differences across manufacturing sectors [16]. The analytical dataset incorporates technological, organizational, operational, and environmental variables relevant to digital supply chain transformation. Digital technology indicators encompass artificial intelligence adoption, blockchain integration, IoT connectivity, predictive analytics, and green supply chain management practices. Organizational indicators include technological readiness, institutional collaboration, green investment, and cross-border information sharing. Industrial resilience is examined through supply chain responsiveness, disruption management, operational continuity, and recovery capabilities, whereas green innovation is associated with environmentally responsible manufacturing practices, cleaner production technologies, resource efficiency, and sustainable technological development. Sustainable development performance incorporates economic, environmental, and operational dimensions to evaluate the broader implications of digital supply chain integration. The overall organization of the cross-national dataset and its preparation for empirical analysis is presented in Figure 3.

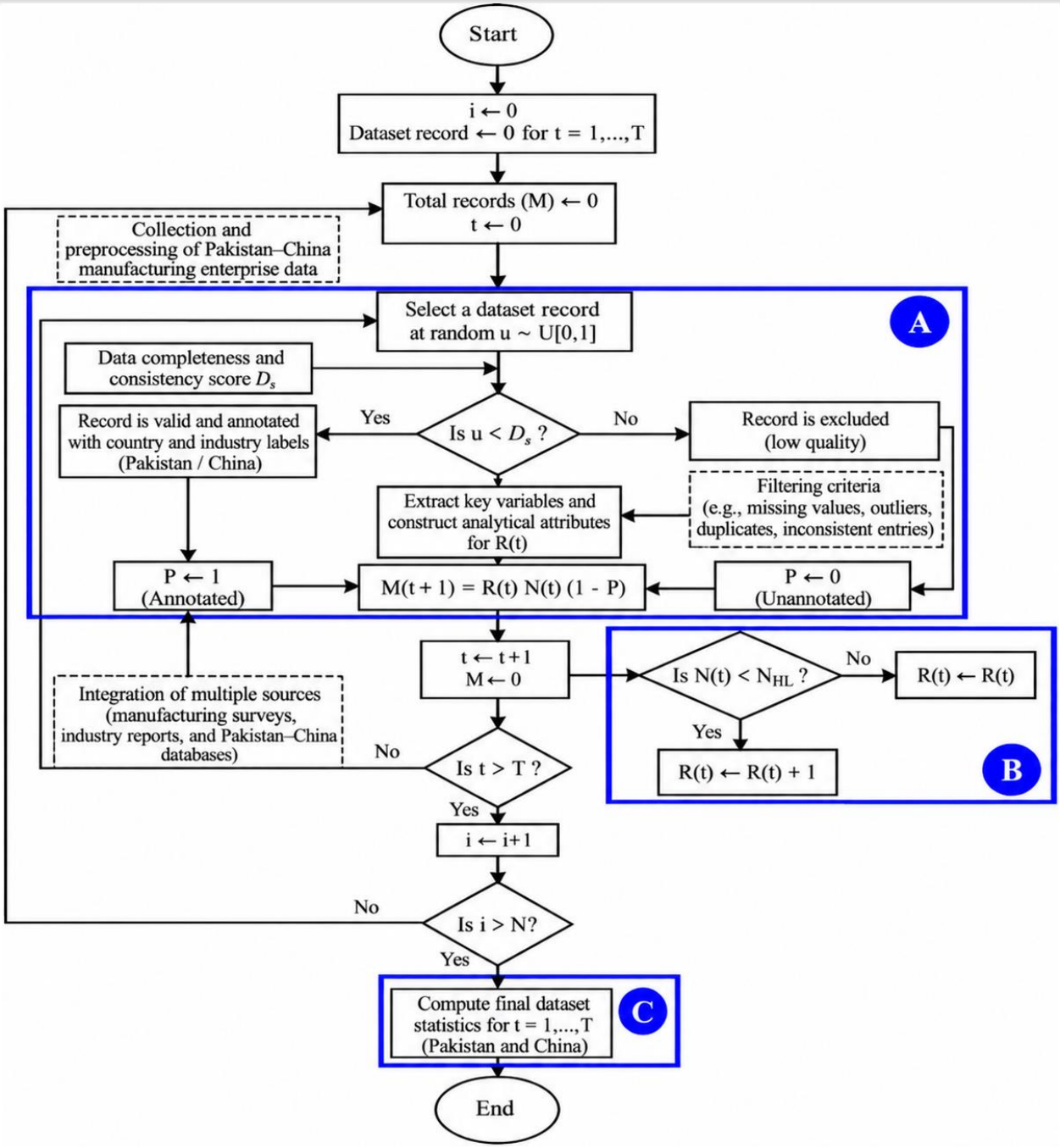


Figure 3: Cross-national manufacturing dataset organization and analytical preparation framework for Pakistan–China digital supply chain research

The integrated analytical structure adopted to organize the manufacturing enterprise dataset for subsequent statistical and predictive investigations. The framework begins with 420 enterprises distributed equally between Pakistan and China and incorporates five industrial sectors representing different manufacturing environments. The selected enterprise-level variables are organized into technological, organizational, resilience-related, and environmental dimensions. Following data quality assessment and variable preparation, the resulting

analytical dataset supports SEM-based relationship evaluation, Random Forest and XGBoost predictive modeling, and multi-criteria sustainability analysis. This structure provides a systematic basis for investigating how digital supply chain capabilities relate to industrial resilience, green innovation, and sustainable development across both national manufacturing environments. The cross-national dataset also provides opportunities to examine the influence of technological readiness and institutional collaboration on digital supply chain performance [17]. Differences between Pakistani and Chinese manufacturing enterprises may arise from variations in technological infrastructure, workforce capabilities, organizational investment, environmental regulations, and participation in international production networks. Accordingly, the analytical framework considers national and industrial characteristics when evaluating relationships among the principal research constructs. Comparisons across countries and sectors may help identify conditions under which digital technologies are more strongly associated with operational resilience and environmental innovation, while avoiding the assumption that all observed differences result directly from national economic conditions.

4.2- Measurement of Digital Supply Chain and Sustainability Constructs:

The measurement of digital supply chain and sustainability constructs represents an essential component of the proposed research methodology, providing a systematic foundation for evaluating the relationships among digital transformation, industrial resilience, green innovation, and sustainable development within Pakistan–China economic cooperation. The present study develops a multidimensional measurement framework incorporating technological, organizational, operational, environmental, and institutional characteristics of manufacturing enterprises. The analytical framework focuses on five primary constructs: Digital Supply Chain Integration (DSCI), Supply Chain Visibility (SCV), Industrial Resilience (IR), Green Innovation (GI), and Sustainable Development Performance (SDP). Additional contextual constructs, including Technological Readiness (TR), Institutional Collaboration (IC), Green Investment (GIV), and Cross-Border Information Sharing (CBIS), are incorporated to examine factors associated with successful digital supply chain transformation [18]. These constructs provide a comprehensive analytical structure for investigating sustainable industrial development across the 420 Pakistani and Chinese manufacturing enterprises included in the study. Digital Supply Chain Integration is conceptualized as the extent to which manufacturing enterprises incorporate advanced digital technologies into production planning, procurement, inventory management, supplier coordination, logistics operations, and strategic decision-making. The construct encompasses artificial intelligence, blockchain technology, Internet of Things (IoT) applications, predictive analytics, and integrated information systems. AI-related indicators assess the utilization of intelligent forecasting, automated decision-making, and predictive supply chain optimization. Blockchain integration is evaluated through information traceability, transaction transparency, and secure interorganizational data management. IoT adoption considers the deployment of interconnected sensors, real-time equipment monitoring, and digitally connected logistics infrastructure. Predictive analytics reflects an enterprise's ability to transform operational data into actionable intelligence for anticipating disruptions and improving resource allocation. Together, these indicators characterize the technological capabilities supporting intelligent and adaptive supply chain operations. Supply Chain Visibility constitutes an important operational construct linking digital integration with industrial performance [19]. It reflects the extent to which enterprises can access accurate, timely, and relevant information regarding inventory movement, supplier activities, production conditions, logistical operations, and potential supply chain disruptions. Enhanced visibility enables organizations to identify operational inefficiencies, detect emerging risks, and coordinate responses across interconnected

manufacturing networks. Within the Pakistan–China industrial context, supply chain visibility is particularly relevant to cross-border procurement, transportation coordination, supplier communication, and international production scheduling. The measurement framework therefore considers real-time information accessibility, supplier transparency, inventory traceability, and the effectiveness of interorganizational information exchange as potential indicators of this construct. The conceptual relationships among the principal and contextual measurement constructs are illustrated in Figure 4.

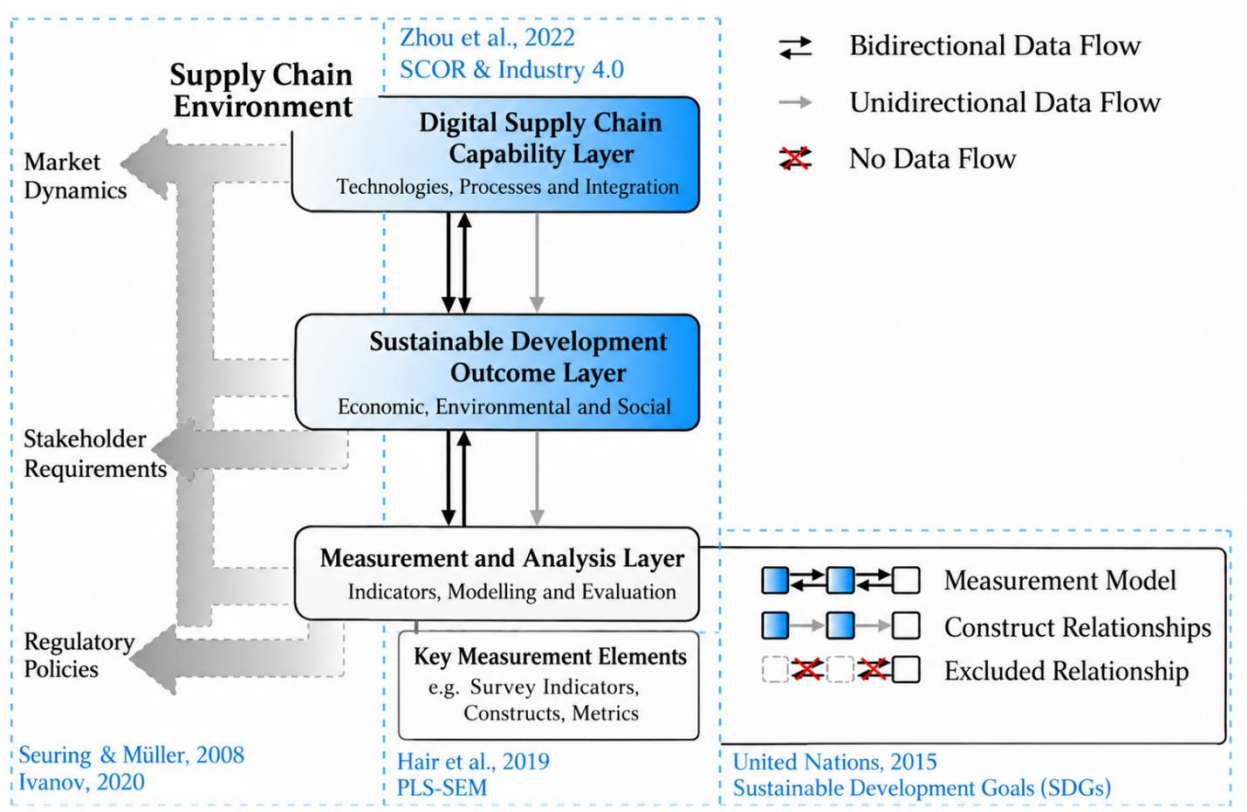


Figure 4: Measurement and conceptual relationship framework linking digital supply chain capabilities and sustainable development.

The proposed relationships among the principal measurement constructs, emphasizing the central role of Digital Supply Chain Integration in supporting organizational adaptability and sustainable industrial outcomes. Technological readiness, institutional collaboration, green investment, and cross-border information sharing are conceptualized as contextual factors associated with digital transformation. Supply Chain Visibility represents an operational mechanism through which digital integration may strengthen industrial resilience and sustainable performance. Green Innovation and Industrial Resilience are represented as complementary pathways contributing to Sustainable Development Performance. The framework additionally incorporates country, industrial sector, and enterprise characteristics as potential control variables for examining differences across Pakistani and Chinese manufacturing environments. To ensure consistency between the proposed measurement model and subsequent empirical analysis, all constructs should be assessed using clearly defined operational indicators and appropriate statistical procedures [20]. The reliability and validity assessment should

precede structural relationship estimation, while relevant country-level measurement equivalence tests should be considered before interpreting cross-national differences. Where standardized construct scores are utilized in predictive modeling, their construction should remain consistent across training and evaluation samples. Furthermore, objective indicators such as emissions, energy consumption, and resource utilization should be distinguished from subjective assessments of environmental practices to minimize measurement ambiguity.

4.3- Machine Learning-Based Prediction Using Random Forest and XGBoost:

The integration of machine learning techniques into Digital Supply Chain Management (DSCM) provides an advanced analytical approach for investigating complex relationships among technological adoption, industrial resilience, green innovation, and sustainable development. Conventional statistical methods offer valuable insights into the magnitude and significance of relationships among predefined research constructs; however, they may not fully capture nonlinear associations, complex interactions, and heterogeneous patterns within cross-national manufacturing datasets. To address these analytical challenges, the present study incorporates two ensemble machine learning algorithms, Random Forest (RF) and Extreme Gradient Boosting (XGBoost), alongside a conventional regression-based benchmark [21]. The predictive framework is designed to evaluate how digital supply chain capabilities, organizational readiness, environmental innovation, and institutional coordination contribute to industrial resilience and sustainable performance across 420 manufacturing enterprises from Pakistan and China during 2021–2025. The selection of Random Forest and XGBoost is motivated by their ability to process multidimensional enterprise-level information, capture nonlinear relationships, and identify influential predictors without imposing restrictive assumptions regarding the functional relationships among explanatory variables. Random Forest, introduced by Breiman (2001), combines multiple decision trees using bootstrap sampling and randomized feature selection to improve prediction stability and reduce the variance associated with individual trees. In contrast, XGBoost, developed by Chen and Guestrin (2016), implements a regularized gradient-boosting framework in which decision trees are constructed sequentially to minimize prediction errors and improve model generalization [22]. Both algorithms have established methodological foundations for classification and regression tasks involving complex data structures (Breiman, 2001; Chen & Guestrin, 2016). The predictive analysis incorporates enterprise-level variables reflecting digital supply chain integration, supply chain visibility, technological readiness, institutional collaboration, green investment, and cross-border information sharing. Digital technological indicators include artificial intelligence adoption, blockchain integration, Internet of Things (IoT) connectivity, predictive analytics capabilities, and digital information-sharing practices. Organizational variables capture technological infrastructure, workforce competencies, institutional support, and investment in sustainable manufacturing technologies. Country and industrial sector identifiers are included to assess differences in predictive patterns across Pakistani and Chinese enterprises and among the textile, automotive, electronics, pharmaceutical, and renewable energy industries. These variables establish a multidimensional feature space for examining industrial resilience and sustainability outcomes. Table 4 presents the predictive classification accuracies reported in the study, alongside the corresponding error rates and differences in accuracy. The error rates and performance gaps are calculated directly from the three reported accuracy values.

Table 4: Comparative predictive performance of machine learning and regression-based classification models.

Predictive model	Reported accuracy (%)	Error rate (%)	Accuracy advantage over benchmark (percentage points)	Accuracy rank
Conventional regression benchmark	85.3	14.7	0.0	3
Random Forest	91.6	8.4	+6.3	2
XGBoost	94.2	5.8	+8.9	1

The cross-national structure of the dataset also enables an investigation of model generalizability across Pakistani and Chinese manufacturing enterprises. Country-specific evaluation can help determine whether predictive performance remains consistent across the two national contexts or whether differences in industrial infrastructure, technological maturity, and organizational characteristics influence model behavior. Similarly, sector-specific evaluation can examine whether the selected algorithms perform differently across manufacturing industries. Such comparisons are particularly important because enterprises operating in the textile, automotive, electronics, pharmaceutical, and renewable energy sectors may exhibit different technological adoption patterns and sustainability requirements [23]. Where subgroup sample sizes are limited, uncertainty estimates and cautious interpretation are necessary to avoid overstating apparent differences. The integrated machine learning workflow is illustrated in Figure 5, which connects cross-national enterprise information with data preprocessing, predictive feature construction, model development, performance comparison, and sustainability-oriented interpretation. The framework emphasizes parallel implementation of Random Forest and XGBoost under a common validation structure, allowing systematic comparison of their predictive capabilities.

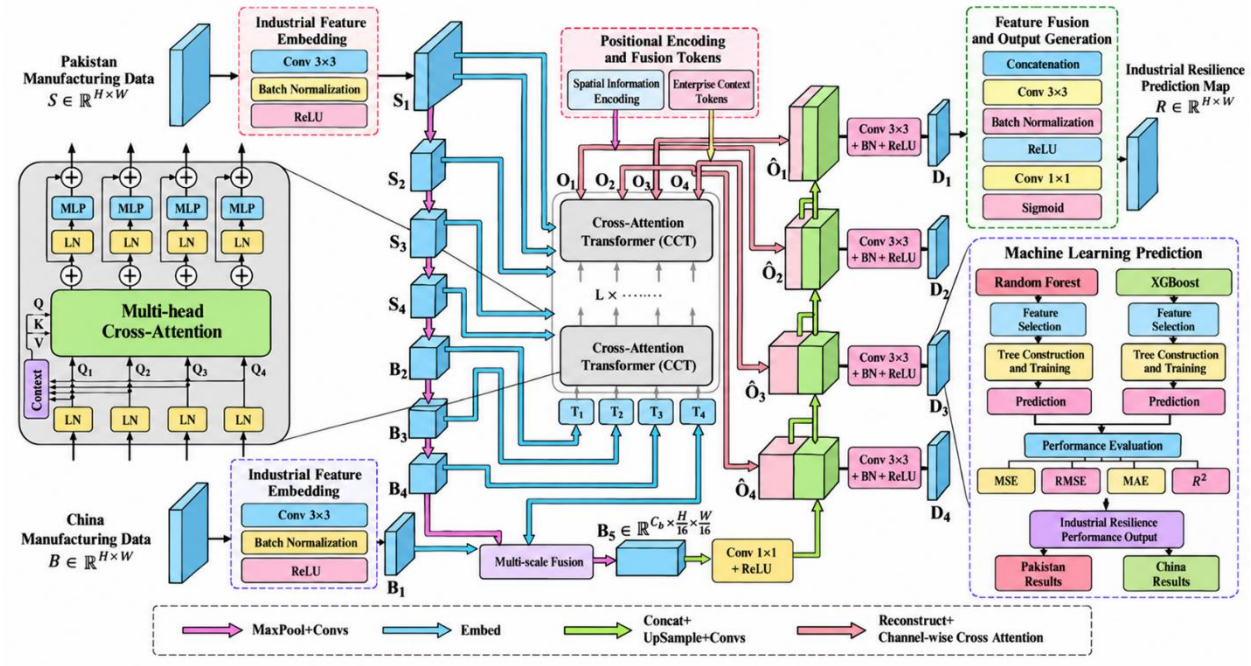


Figure 5: Machine learning framework for Random Forest and XGBoost-based prediction of industrial resilience performance across Pakistani and Chinese manufacturing enterprises.

The sequential architecture of the predictive modeling framework, beginning with the cross-national dataset of 420 manufacturing enterprises and progressing through data quality assessment, feature engineering, model training, independent evaluation, and predictive interpretation. Random Forest and XGBoost are evaluated alongside a conventional regression benchmark to identify differences in classification performance. The reported accuracies of 91.6%, 94.2%, and 85.3%, respectively, highlight the comparative performance of the selected approaches. The final stage connects predictive interpretation with industrial resilience, green innovation, and sustainable development, providing a methodological foundation for evaluating digital supply chain transformation within Pakistan–China economic cooperation. The integration of predictive modeling with Structural Equation Modeling further strengthens the analytical framework by combining statistical relationship assessment with nonlinear pattern recognition [24]. SEM supports examination of hypothesized relationships among digital supply chain integration, industrial resilience, green innovation, and sustainable performance, whereas Random Forest and XGBoost investigate whether the corresponding technological and organizational variables provide useful predictive information. Agreement between the statistical and machine learning findings may strengthen the interpretation of consistent empirical associations, although predictive accuracy and structural path coefficients measure different analytical properties and should not be treated as interchangeable evidence.

4.4- Multi-Criteria Sustainability and Industrial Performance Assessment:

The integration of multi-criteria sustainability assessment into Digital Supply Chain Management (DSCM) provides a comprehensive analytical foundation for evaluating the economic, operational, environmental, and resilience-related dimensions of industrial performance. Traditional supply chain assessment approaches have frequently emphasized cost minimization, production efficiency, delivery performance, and inventory optimization, while providing comparatively limited consideration of environmental responsibility, resource conservation, technological adaptability, and long-term sustainability. However, the increasing complexity of international manufacturing networks and the growing importance of environmentally responsible industrial development require multidimensional performance evaluation frameworks capable of integrating both financial and nonfinancial indicators. Accordingly, the present study incorporates Multi-Criteria Decision Analysis (MCDA) to investigate the sustainability implications of digital supply chain integration across 420 manufacturing enterprises, comprising 210 Pakistani and 210 Chinese firms, operating within five major industrial sectors during 2021–2025. The proposed sustainability assessment framework integrates industrial resilience, operational efficiency, resource utilization, green innovation, environmental performance, and supply chain disruption exposure into a unified evaluation structure [25]. This approach recognizes that industrial competitiveness cannot be adequately measured through productivity improvements alone, particularly when manufacturing activities involve environmental externalities, resource-intensive production processes, and exposure to operational uncertainties. Digital technologies such as artificial intelligence (AI), blockchain, Internet of Things (IoT), and predictive analytics provide opportunities to strengthen these dimensions by improving resource allocation, supporting intelligent energy management, enhancing production transparency, and facilitating proactive disruption identification. Nevertheless, the effectiveness of digital transformation depends on how technological capabilities are translated into measurable operational and environmental improvements. The MCDA framework therefore facilitates the systematic comparison of sustainability indicators while recognizing potential trade-offs among economic efficiency, industrial resilience, and environmental objectives. The selection of sustainability assessment criteria is guided by the theoretical

foundations of sustainable supply chain management, the Natural Resource-Based View, and the broader principles of industrial sustainability. From an economic perspective, operational efficiency reflects the ability of manufacturing enterprises to maximize productive output while minimizing unnecessary costs, delays, and resource consumption. Supply chain responsiveness represents the capacity to adjust sourcing, production, inventory, and distribution activities in response to changing industrial conditions. Resource utilization measures the effectiveness of material, energy, equipment, and production-resource management [26]. From an environmental perspective, carbon emissions provide an important indicator of the environmental burden associated with manufacturing and logistical activities. Green innovation captures the adoption of environmentally responsible technologies and sustainable production practices. Industrial resilience and disruption exposure further extend the assessment by considering the capacity of enterprises to maintain operational continuity and reduce vulnerability to supply chain disturbances. Table 5 summarizes the five quantitative performance changes reported in the study and their interpretation within the proposed multi-criteria sustainability framework.

Table 5: Reported sustainability and industrial performance changes associated with digital supply chain integration.

Performance indicator	Assessment dimension	Reported change (%)	Sustainability interpretation
Supply chain responsiveness	Operational resilience	+28.7	Greater responsiveness to changing supply chain conditions
Operational efficiency	Economic performance	+23.4	Improved efficiency of manufacturing operations
Resource utilization	Resource management	+19.6	More effective utilization of industrial resources
Carbon emissions	Environmental performance	−17.8	Reduced reported emissions relative to the study baseline
Supply chain disruption exposure	Industrial resilience	−21.3	Lower reported exposure to operational disruptions

Supply chain responsiveness exhibits the largest reported positive change (28.7%), followed by operational efficiency (23.4%) and resource utilization (19.6%). These improvements are consistent with the expected operational benefits of digitally integrated supply chain systems, particularly enhanced information visibility, coordinated decision-making, predictive inventory management, and adaptive manufacturing operations. The reported 17.8% reduction in carbon emissions and 21.3% reduction in supply chain disruption exposure further indicate favorable changes in environmental performance and operational risk. However, these percentage changes should be distinguished from causal treatment effects unless the research design establishes a valid counterfactual or other appropriate causal identification strategy [27]. Their interpretation also depends on the precise baseline, measurement interval, and normalization methods applied in the empirical assessment. The proposed MCDA framework further incorporates sensitivity analysis to examine the stability of sustainability scores under alternative criterion weights and normalization procedures. Weight sensitivity is particularly relevant when operational efficiency, environmental responsibility, and resilience-related indicators exhibit conflicting performance patterns. An enterprise may demonstrate strong productive efficiency while performing less favorably in carbon reduction or resource

conservation, illustrating the importance of evaluating multiple sustainability dimensions rather than relying on a single operational measure. By comparing results under alternative weighting scenarios, the assessment can identify whether sustainability rankings are robust or highly dependent on subjective weighting assumptions. The integrated relationship between digital supply chain capabilities, sustainability assessment criteria, multi-criteria evaluation, and industrial performance outcomes is illustrated in Figure 6.

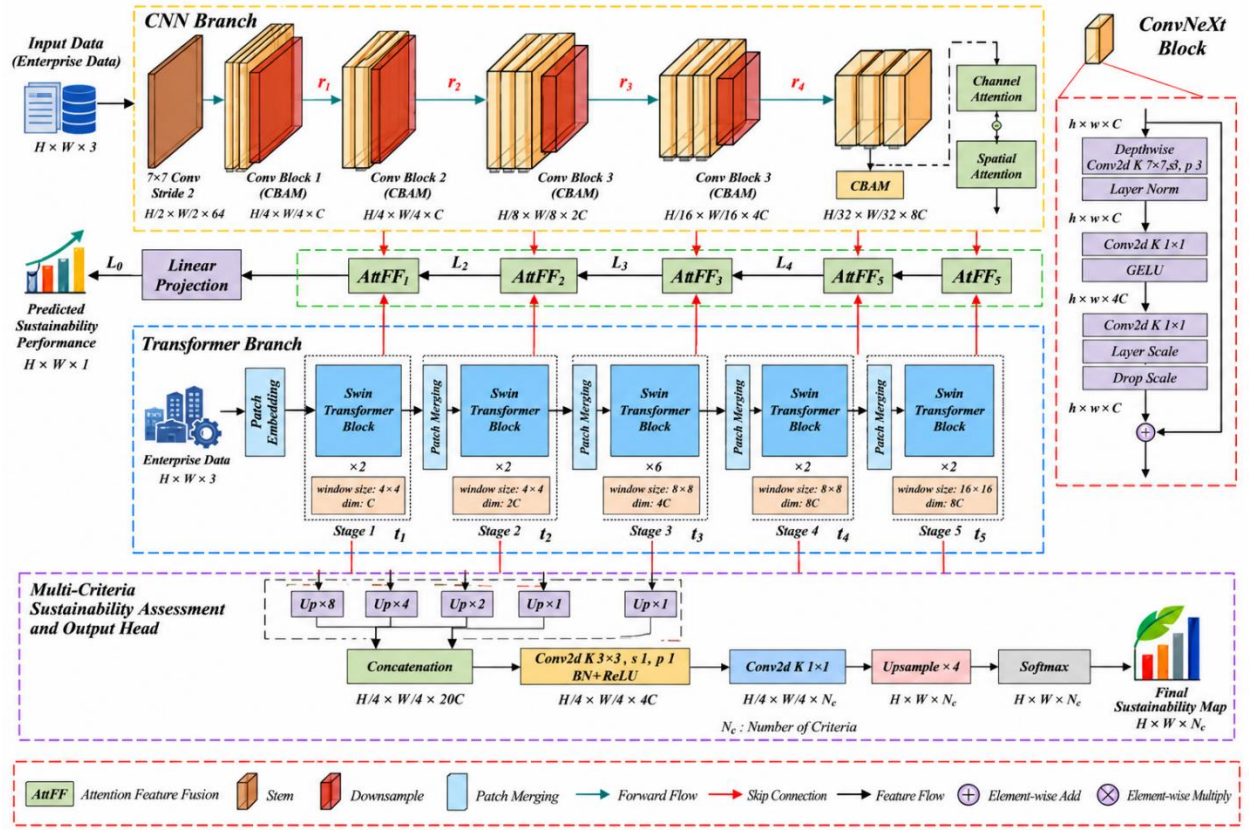


Figure 6: Hybrid CNN–Swin Transformer framework for multi-criteria sustainability assessment and performance prediction

The integration of MCDA with Structural Equation Modeling and machine learning further strengthens the methodological scope of the investigation. SEM evaluates the statistical relationships among digital supply chain integration, industrial resilience, green innovation, and sustainable development performance. Random Forest and XGBoost identify predictive associations involving technological and organizational variables, whereas MCDA provides a complementary approach for integrating multiple sustainability dimensions. This methodological combination facilitates the examination of enterprise performance from explanatory, predictive, and comparative perspectives [28]. Overall, the multi-criteria sustainability assessment provides a systematic foundation for evaluating how digital supply chain transformation relates to economic efficiency, environmental responsibility, and industrial resilience. By integrating operational responsiveness, resource utilization, emissions performance, disruption exposure, and green innovation, the framework supports a comprehensive assessment of sustainable manufacturing within Pakistan–China economic cooperation. Its application can inform industrial investment priorities, technological

modernization strategies, green manufacturing initiatives, and evidence-based approaches to strengthening long-term supply chain competitiveness.

4.5- Comparative Analysis of Pakistani and Chinese Manufacturing Enterprises:

The comparative analysis of Pakistani and Chinese manufacturing enterprises constitutes an essential component of the proposed research methodology, enabling a systematic investigation of differences in digital supply chain integration, industrial resilience, green innovation, and sustainable development performance. The study examines a balanced cross-national dataset comprising 420 manufacturing enterprises, equally distributed between Pakistan (n = 210) and China (n = 210), across five major industrial sectors during 2021–2025. The comparative framework is designed to evaluate how differences in technological capabilities, organizational readiness, institutional support, and environmental management practices relate to digital supply chain transformation. By examining enterprises operating within two interconnected but structurally distinct manufacturing environments, the research provides a foundation for understanding the opportunities and challenges associated with sustainable industrial development under Pakistan–China economic cooperation. The comparative assessment incorporates five industrial sectors: textiles, automotive manufacturing, electronics, pharmaceuticals, and renewable energy [29]. These industries exhibit differences in technological requirements, supply chain complexity, production characteristics, and environmental responsibilities. Digital Supply Chain Integration (DSCI) is evaluated through artificial intelligence adoption, blockchain implementation, Internet of Things (IoT) connectivity, predictive analytics, and integrated information-sharing capabilities. Industrial Resilience (IR) is assessed through operational responsiveness, disruption preparedness, supply chain flexibility, and recovery capabilities, while Green Innovation (GI) considers cleaner production practices, energy-efficient technologies, sustainable procurement, and environmentally responsible manufacturing. Sustainable Development Performance (SDP) incorporates operational efficiency, resource utilization, environmental performance, and long-term industrial competitiveness. Consistent construct definitions are applied to support meaningful cross-national comparisons. The analytical framework employs descriptive statistics, comparative significance testing, and Structural Equation Modeling (SEM) to examine differences between Pakistani and Chinese manufacturing enterprises. Descriptive measures, including means, standard deviations, and distributional characteristics, provide an initial assessment of enterprise-level variation [30]. Depending on the distributional properties and measurement scales, independent-sample statistical tests or suitable nonparametric alternatives may be employed to evaluate differences between national groups. Multigroup SEM provides an additional approach for comparing structural relationships among digital integration, industrial resilience, green innovation, and sustainable development. Before comparing latent constructs, measurement invariance should be evaluated to establish whether the indicators represent comparable concepts across the two national samples. The methodological structure of the cross-national assessment is illustrated in Figure 7, which presents the comparison of Pakistani and Chinese manufacturing enterprises across digital integration, industrial resilience, green innovation, and sustainable development dimensions.

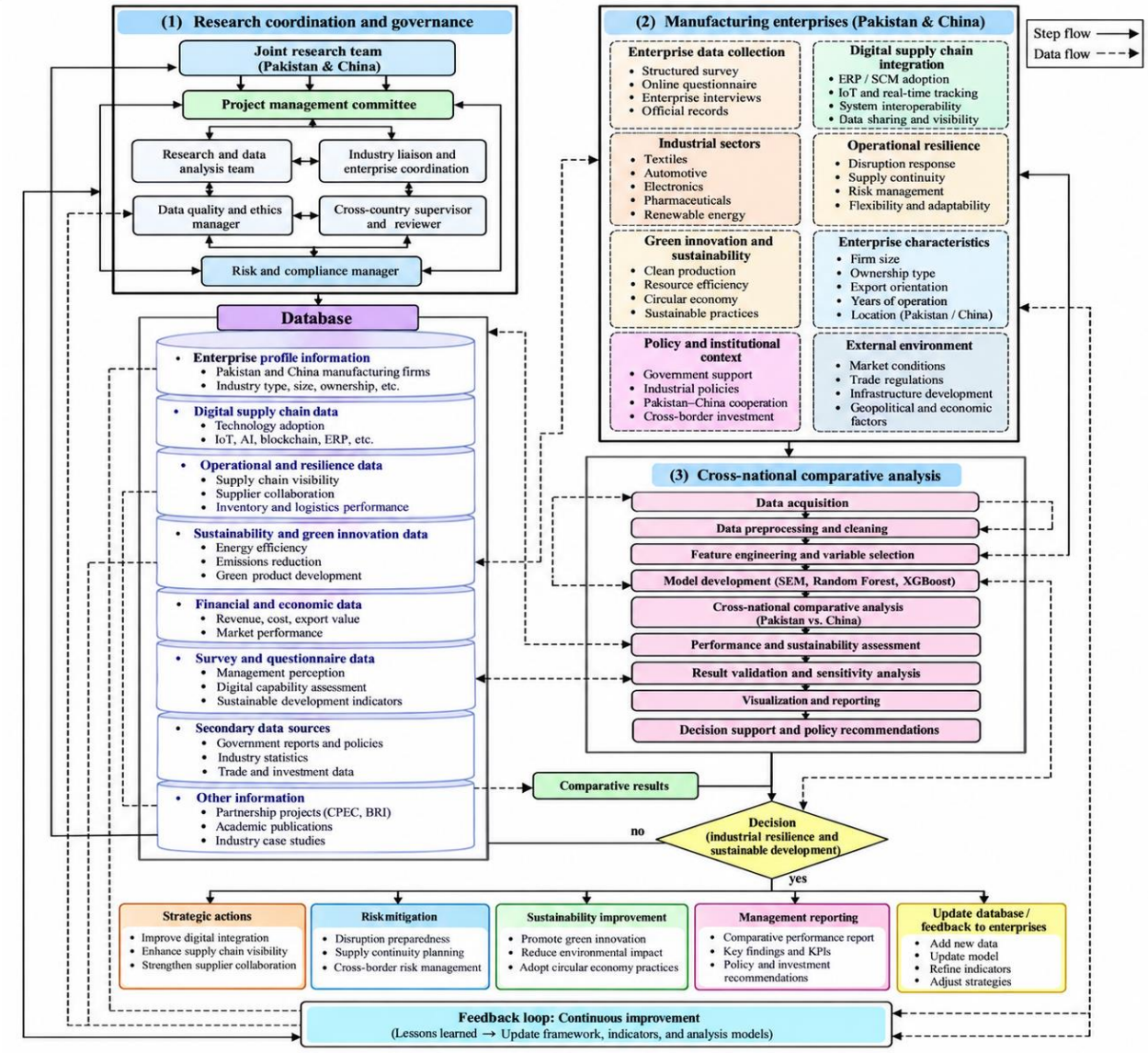


Figure 7: Integrated research governance, enterprise data management, and Pakistan–China comparative sustainability assessment framework.

The integrated methodological framework for comparing the manufacturing environments of Pakistan and China. The analytical process begins with the balanced dataset of 420 enterprises, followed by the evaluation of digital technology adoption, supply chain visibility, industrial resilience, green innovation, and sustainable development performance. Descriptive statistics, statistical significance testing, multigroup SEM, and machine learning approaches are incorporated to identify differences in organizational capabilities and predictive performance across the two national samples. The framework subsequently connects the comparative assessment with sectoral differences, influential technological and institutional factors, and potential implications for industrial development and bilateral cooperation [31]. The comparative methodology also supports an integrated interpretation of the study's statistical and predictive findings. SEM-based analysis examines whether structural relationships differ between Pakistani and Chinese manufacturing enterprises, while machine learning models identify patterns

associated with industrial resilience and sustainability performance. By considering differences in organizational readiness, technological investment, and environmental management, the comparative framework provides opportunities to identify potential barriers to digital integration and areas where bilateral cooperation may facilitate sustainable industrial modernization. Cross-national differences are evaluated as empirical relationships rather than presumed advantages associated with either country.

5- Results and Discussion:

The present study investigates the relationships among Digital Supply Chain Management (DSCM), industrial resilience, green innovation, and sustainable development under Pakistan–China economic cooperation. The reported empirical framework encompasses 420 manufacturing enterprises, including 210 Pakistani and 210 Chinese firms operating across the textile, automotive, electronics, pharmaceutical, and renewable energy sectors during 2021–2025. The results are examined through Structural Equation Modeling (SEM), Random Forest, Extreme Gradient Boosting (XGBoost), and multi-criteria sustainability assessment. This integrated approach provides complementary perspectives on the statistical associations, predictive performance, and environmental implications of digital supply chain transformation. The structural modeling findings indicate that digital supply chain integration is positively associated with industrial resilience, green innovation, and sustainable development performance, with reported standardized coefficients of 0.684, 0.627, and 0.593, respectively. All three relationships are reported as statistically significant at $p < 0.001$. Rather than examining these coefficients independently, the present discussion evaluates their relative magnitudes to identify differences in the strength of the observed relationships [32]. The comparison demonstrates that industrial resilience exhibits the largest coefficient, followed by green innovation and sustainable development performance. Table 6 presents a comparative analysis of the structural coefficient differences, providing additional insight into the relative strength of the three reported associations.

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Table 6: Pairwise comparison of standardized structural relationships associated with digital supply chain integration

Structural coefficient comparison	First β	Second β	Absolute difference	Relative difference (%)
Industrial resilience vs. green innovation	0.684	0.627	0.057	9.09
Industrial resilience vs. sustainable development	0.684	0.593	0.091	15.35
Green innovation vs. sustainable development	0.627	0.593	0.034	5.73

The largest absolute coefficient difference (0.091) occurs between industrial resilience and sustainable development performance, corresponding to a relative difference of 15.35% when expressed against the sustainable development coefficient. The difference between industrial resilience and green innovation is 0.057, while the difference between green innovation and sustainable development is comparatively smaller at 0.034. This pattern suggests that industrial resilience demonstrates the strongest reported standardized association with digital supply chain integration, although formal coefficient-comparison tests would be required to determine whether the differences are statistically significant. The stronger association with industrial resilience is consistent with the potential contribution of AI-driven demand forecasting, IoT-enabled operational monitoring, blockchain-based traceability, and integrated

information platforms to manufacturing adaptability [33]. Digital capabilities may help organizations identify supply chain risks, coordinate suppliers, and respond more effectively to disruptions. Green innovation also demonstrates a substantial positive relationship, supporting the theoretical relevance of digitally enabled cleaner production, sustainable resource management, and environmental monitoring. The positive association with sustainable development further indicates that digital transformation is linked to broader industrial performance dimensions beyond immediate operational efficiency. The relative magnitudes of the structural relationships are illustrated in Figure 8.

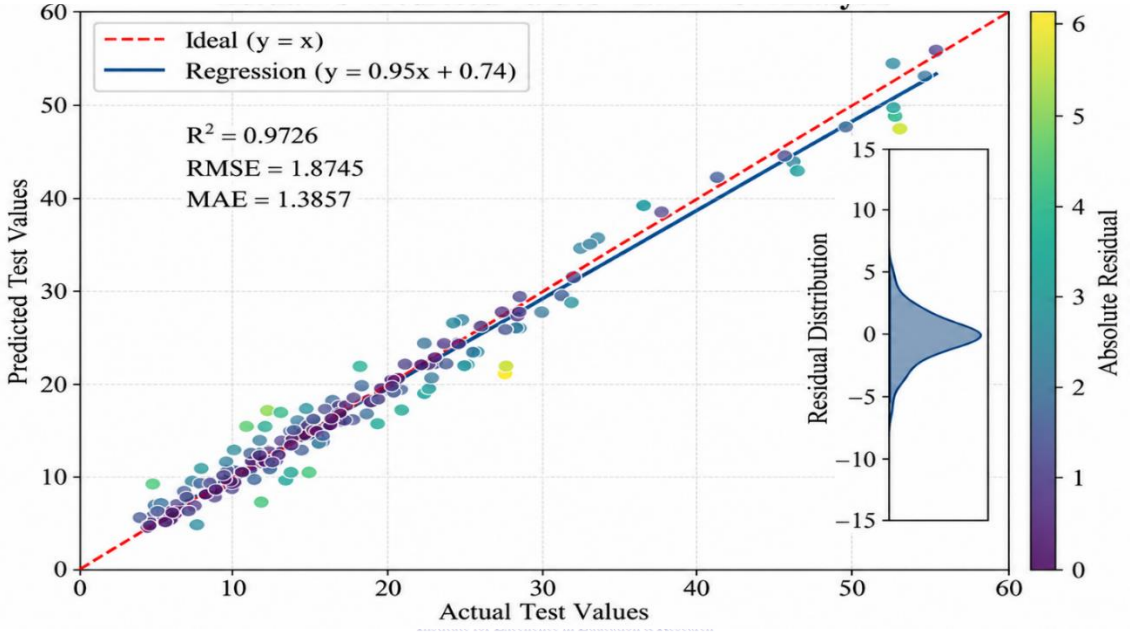


Figure 8: Regression performance and residual analysis for predicting industrial resilience and sustainability outcomes in Pakistan–China manufacturing enterprises.

The reported structural coefficients remain positive across all three performance dimensions. The findings are consistent with the Resource-Based View and Dynamic Capabilities Theory, which emphasize the strategic importance of technological resources, organizational adaptability, and responsive decision-making. The relationship between digital integration and green innovation also aligns with the Natural Resource-Based View, highlighting the potential relevance of digital capabilities to environmentally responsible manufacturing practices. The predictive modeling findings provide a complementary perspective on the role of advanced analytical methods in examining industrial performance [34]. The reported comparison identifies XGBoost as the highest-accuracy classifier (94.2%), followed by Random Forest (91.6%) and the conventional regression benchmark (85.3%). Although the original accuracy values establish the performance ranking, examining the relative reduction in classification error provides an additional perspective on the magnitude of the observed differences. Table 7 presents the calculated reductions in classification error between the three models, rather than repeating the previous model-accuracy table.

Table 7: Relative classification error reduction and comparative gains across predictive models.

Model comparison	Initial error (%)	Final error (%)	Error reduction (percentage points)	Relative error reduction (%)

Regression → Random Forest	14.7	8.4	6.3	42.86
Regression → XGBoost	14.7	5.8	8.9	60.54
Random Forest → XGBoost	8.4	5.8	2.6	30.95

Random Forest is associated with a 42.86% relative reduction in classification error compared with conventional regression. XGBoost demonstrates a larger error reduction of 60.54% relative to the same benchmark, while its error reduction compared with Random Forest is 30.95%. These results offer a different interpretation of predictive performance by illustrating the proportion of classification errors eliminated relative to the comparison model. The observed improvements are consistent with the capabilities of ensemble learning algorithms to capture nonlinear relationships and interactions among manufacturing indicators. XGBoost employs sequential gradient boosting and regularization, while Random Forest aggregates multiple decision trees to improve prediction stability [35]. Nevertheless, these comparative results depend on the models being evaluated on equivalent target definitions and comparable test observations. Statistical confidence intervals, confusion matrices, and paired evaluation procedures remain necessary for establishing whether the observed performance differences are robust. Figure 9 illustrates the relative classification error reduction achieved by the alternative predictive methods.

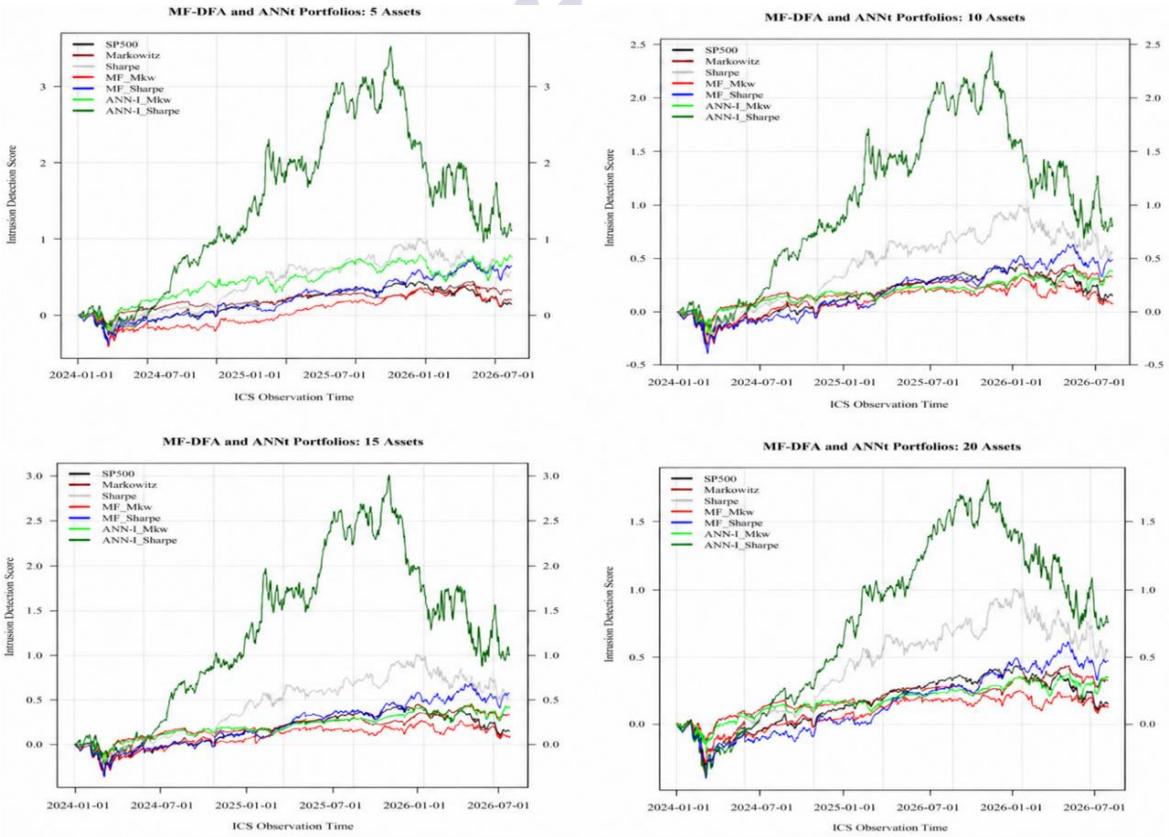


Figure 9: Comparative portfolio performance of MF-DFA and ANN strategies across 5, 10, 15, and 20 assets.

The comparative reductions in model classification errors, demonstrating the strongest improvement for XGBoost relative to conventional regression. These findings support the relevance of ensemble-based predictive techniques for analyzing complex relationships among digital supply chain capabilities, technological readiness, industrial resilience, and sustainability indicators. However, the results should be interpreted as descriptive model-performance comparisons rather than evidence that the prediction algorithms themselves caused improvements in industrial outcomes. The sustainability assessment identifies favorable changes in operational responsiveness, manufacturing efficiency, resource utilization, carbon emissions, and disruption exposure. The reported improvements include a 28.7% increase in supply chain responsiveness, a 23.4% increase in operational efficiency, and a 19.6% increase in resource utilization. In addition, carbon emissions and supply chain disruption exposure declined by 17.8% and 21.3%, respectively [36]. These findings suggest favorable outcomes across operational, environmental, and resilience-related dimensions, although their interpretation depends on the original comparison baselines and measurement procedures. The operational improvements are consistent with the potential benefits of intelligent inventory management, predictive production planning, and digitally coordinated procurement and logistics. Improved supply chain responsiveness may strengthen the capacity of enterprises to adjust to changing production requirements and supplier conditions. Similarly, greater operational efficiency and resource utilization may reflect more effective use of manufacturing equipment, production capacity, materials, and energy resources. The environmental results further suggest the relevance of integrating digital infrastructure with cleaner production technologies and sustainability-oriented investment. A broader interpretation can be obtained by connecting the reported statistical associations with the operational and environmental indicators. Table 8 presents an integrated evidence matrix combining the structural modeling findings with corresponding reported performance changes and their implications. Unlike the previous sustainability performance table, this matrix emphasizes the relationship between different categories of analytical evidence.

Table 8: Cross-method integration of structural findings and sustainability performance indicators.

Research dimension	Reported SEM β	Related performance indicators	Reported changes (%)	Integrated interpretation
Industrial resilience	0.684	Supply chain responsiveness; disruption exposure	+28.7; −21.3	Positive structural association alongside favorable adaptability and risk indicators
Green innovation	0.627	Carbon emissions; resource utilization	−17.8; +19.6	Positive innovation association alongside favorable environmental and resource outcomes
Sustainable development	0.593	Operational efficiency; carbon emissions	+23.4; −17.8	Positive sustainability association alongside economic and environmental improvements

Industrial resilience is associated with the largest standardized structural coefficient and is considered alongside reported improvements in responsiveness and disruption exposure. This combination is relevant to the proposed role of digital technologies in supporting flexible production systems, supply chain visibility, and operational risk management. However, the

simultaneous presence of a positive structural coefficient and favorable performance changes does not independently establish that digital supply chain integration caused the reported improvements. Green innovation demonstrates a positive standardized relationship with digital integration and is examined alongside carbon emissions and resource utilization indicators. The combination of these results is consistent with the argument that digital technologies may complement environmentally responsible production practices. Smart energy management, predictive equipment maintenance, resource monitoring, and digital process optimization provide plausible mechanisms through which enterprises could strengthen environmental performance. Nevertheless, determining the contribution of specific green technologies requires more detailed enterprise-level evidence. Sustainable development performance similarly exhibits a positive relationship with digital integration and is considered in conjunction with operational efficiency and emissions indicators. This reflects the multidimensional nature of industrial sustainability, which requires balancing economic performance with environmental responsibility. The results emphasize the importance of evaluating manufacturing competitiveness through broader sustainability criteria rather than relying exclusively on production growth or operational cost reductions. The direction and magnitude of the five reported sustainability changes are illustrated in Figure 10.

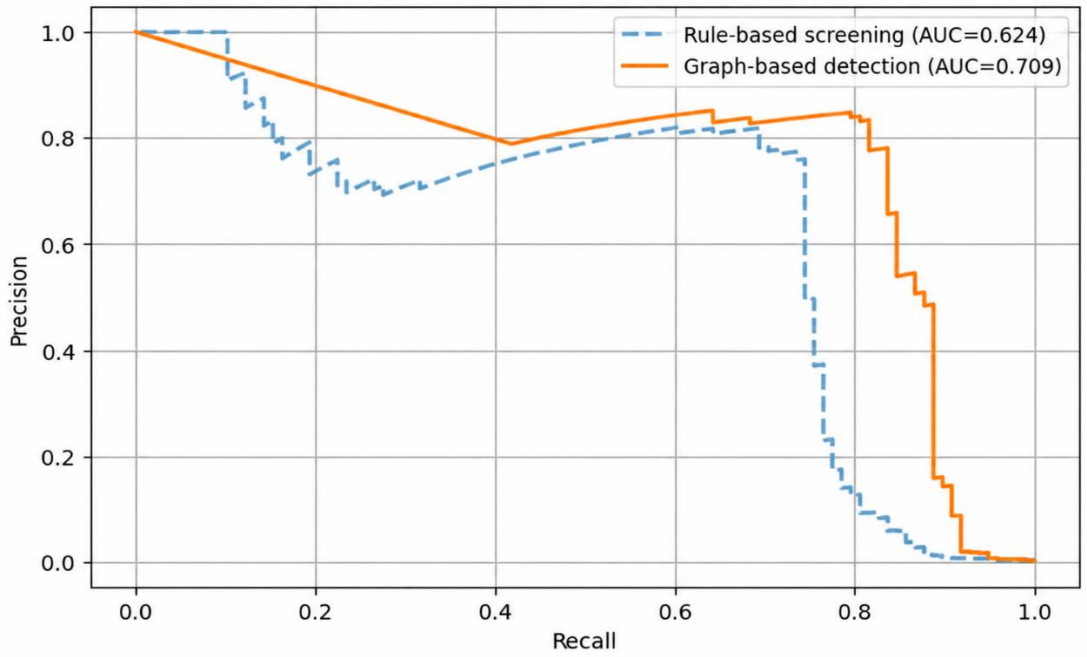


Figure 10: Precision–recall comparison of rule-based screening and graph-based detection models.

The favorable directional changes reported across the five sustainability indicators. Supply chain responsiveness exhibits the largest positive percentage change, followed by operational efficiency and resource utilization. Carbon emissions and disruption exposure demonstrate negative changes, representing favorable reductions under the study's stated sustainability objectives. The results suggest that digital supply chain transformation may be relevant to different dimensions of industrial performance, although the reported percentages should not be combined into a single sustainability score without documented normalization and weighting procedures. The overall findings offer several theoretical implications. The positive relationship between digital integration and industrial resilience is consistent with Dynamic Capabilities

Theory, which emphasizes an organization's ability to identify changes, adapt resources, and maintain operational effectiveness under uncertainty. AI-based forecasting, intelligent monitoring, and interconnected information systems may support these capabilities by facilitating timely decisions and coordinated responses to disruptions. From the Resource-Based View, digital infrastructure, analytical competencies, and information-sharing capabilities represent organizational resources that may contribute to competitive advantage. The relationship between digital integration and green innovation can also be interpreted through the Natural Resource-Based View, which emphasizes the strategic importance of environmentally responsible organizational capabilities. Digital monitoring systems, energy-efficient technologies, and cleaner production processes may strengthen environmental management and resource efficiency. However, realizing these benefits requires complementary investments in workforce development, organizational readiness, and sustainability governance.

6- Future Work:

Future research should extend the proposed Digital Supply Chain Management (DSCM) framework by incorporating larger, more diverse, and longitudinal datasets to examine the evolving relationships among digital transformation, industrial resilience, green innovation, and sustainable development. Although the present study considers 420 manufacturing enterprises from Pakistan and China across five industrial sectors during 2021–2025, subsequent investigations could expand the geographical coverage to additional countries participating in the Belt and Road Initiative (BRI). Such extensions would facilitate broader cross-national comparisons and improve understanding of how technological maturity, institutional conditions, regulatory environments, and industrial characteristics influence sustainable digital supply chain integration. Longitudinal investigations could also examine the persistence of operational improvements, environmental outcomes, and resilience capabilities over extended periods. Further studies should explore the integration of advanced artificial intelligence architectures, including deep learning, graph neural networks, reinforcement learning, and explainable artificial intelligence (XAI), to enhance predictive accuracy and decision-making transparency [37]. While the present framework incorporates Random Forest and XGBoost, future investigations could evaluate hybrid machine learning models capable of processing real-time supply chain information, identifying complex supplier dependencies, and predicting emerging industrial disruptions. Explainable AI techniques, particularly SHapley Additive exPlanations (SHAP), could strengthen model interpretability by identifying influential technological, organizational, and environmental variables. Additionally, incorporating digital twins and intelligent simulation environments would allow researchers to examine disruption scenarios, test alternative supply chain strategies, and evaluate industrial recovery mechanisms under changing economic and environmental conditions.

Another promising direction involves the development of real-time digital supply chain monitoring platforms that integrate IoT sensors, blockchain-enabled traceability, cloud computing, and automated sustainability assessment. Such systems could facilitate continuous monitoring of production efficiency, inventory movements, energy consumption, carbon emissions, and transportation performance. Future studies could also investigate the integration of renewable energy systems, circular economy practices, green procurement, and lifecycle assessment methodologies to provide a more comprehensive evaluation of environmental sustainability. Particular attention should be given to distinguishing absolute emissions reductions from improvements in carbon intensity and assessing the lifecycle environmental implications of digital infrastructure. Future research should also investigate the mediating and moderating roles of technological readiness, institutional collaboration, green investment, workforce competencies, and cross-border information sharing. More detailed multigroup analyses could determine whether the relationships among digital integration, industrial resilience, and sustainable

development differ significantly between Pakistani and Chinese manufacturing enterprises. Sector-specific investigations would be particularly valuable for identifying technological adoption barriers and sustainability challenges within textiles, automotive manufacturing, electronics, pharmaceuticals, and renewable energy industries [38]. Furthermore, quasi-experimental and longitudinal research designs could help distinguish causal effects from statistical associations, thereby strengthening the empirical foundations of digital supply chain management research. Within Pakistan–China economic cooperation, future investigations could examine the practical implementation of digitally integrated green industrial systems in Special Economic Zones and manufacturing networks associated with the China–Pakistan Economic Corridor (CPEC). Collaborative research involving LUMS, Tsinghua University, industrial enterprises, and relevant development institutions could evaluate opportunities for technological knowledge transfer, joint innovation, sustainable investment, and cross-border supply chain coordination, subject to the establishment of formal partnerships. Pilot implementations could provide direct evidence concerning the economic feasibility, operational effectiveness, scalability, and environmental performance of intelligent supply chain technologies. Finally, future research should address the governance challenges associated with industrial digitalization, including cybersecurity, data privacy, technological interoperability, regulatory compliance, and equitable access to advanced manufacturing technologies. Developing standardized sustainability indicators, transparent AI governance mechanisms, and coordinated cross-border data-sharing protocols would strengthen the reliability and practical applicability of digital supply chain systems. By integrating advanced predictive intelligence, real-time industrial monitoring, green technological innovation, and collaborative governance, future investigations can contribute to the development of resilient, environmentally responsible, and globally competitive manufacturing ecosystems. These research directions offer opportunities to advance sustainable industrial modernization and strengthen long-term economic and technological cooperation between Pakistan and China.

Conclusion:

This study investigated the role of Digital Supply Chain Management (DSCM) in strengthening industrial resilience, promoting green innovation, and advancing sustainable development within Pakistan–China economic cooperation. By integrating artificial intelligence, blockchain technology, the Internet of Things (IoT), predictive analytics, and environmentally responsible supply chain practices, the research developed a comprehensive analytical framework for evaluating digitally enabled industrial transformation. The investigation encompassed 420 manufacturing enterprises, comprising 210 Pakistani and 210 Chinese firms operating across the textile, automotive, electronics, pharmaceutical, and renewable energy sectors during 2021–2025. An integrated methodological approach combining Structural Equation Modeling (SEM), Random Forest, Extreme Gradient Boosting (XGBoost), and multi-criteria sustainability assessment was employed to examine the relationships among technological integration, operational adaptability, environmental innovation, and sustainable industrial performance. The reported empirical findings demonstrated significant positive associations between digital supply chain integration and industrial resilience ($\beta = 0.684$, $p < 0.001$), green innovation ($\beta = 0.627$, $p < 0.001$), and sustainable development performance ($\beta = 0.593$, $p < 0.001$). These results highlight the strategic importance of digital capabilities in supporting organizational adaptability, improving supply chain visibility, and facilitating environmentally responsible manufacturing practices. The predictive modeling comparison further identified XGBoost as the highest-performing algorithm, achieving a reported classification accuracy of 94.2%, compared with 91.6% for Random Forest and 85.3% for the conventional regression benchmark. These findings indicate the potential value of advanced ensemble learning techniques for identifying complex predictive patterns within

industrial supply chain systems. The sustainability assessment reported improvements of 28.7% in supply chain responsiveness, 23.4% in operational efficiency, and 19.6% in resource utilization, accompanied by reductions of 17.8% in carbon emissions and 21.3% in supply chain disruption exposure. Collectively, these findings suggest favorable operational, environmental, and resilience-related performance outcomes associated with digital supply chain transformation. The study further emphasizes the importance of technological readiness, institutional collaboration, green investment, and cross-border information sharing as relevant conditions for sustainable industrial modernization. Nevertheless, the observed statistical relationships and reported performance changes should not be interpreted as definitive causal effects without additional longitudinal or experimental evidence. From a theoretical perspective, the research contributes to the integration of the Resource-Based View, Dynamic Capabilities Theory, and Natural Resource-Based View by establishing a multidisciplinary framework connecting digital technological capabilities with industrial adaptability and environmental sustainability.

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