

ENHANCING SUSTAINABLE MANUFACTURING SUPPLY CHAIN PERFORMANCE THROUGH INDUSTRY 4.0 TECHNOLOGIES: THE MEDIATING ROLE OF PROCESS INNOVATION IN PAKISTAN'S MANUFACTURING SECTOR

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Abstract

The thesis explores the role of Industry 4.0 technologies in improving the performance of sustainable manufacturing supply chain, and process innovation is among the mediating factors that the research focuses on in the manufacturing sector of Pakistan. Over the past few years, the manufacturing companies in the developing economies like Pakistan have been under pressure to enhance the effectiveness of their supply chains and at the same time achieve the goals of the supply chain of environmental, social and economic sustainability. The use of digital technologies and the Internet of Things (IoT), big data analytics, automation, artificial intelligence, and cyber-physical systems has become the key to Industry 4.0, which can reform the existing manufacturing and supply chain practices. Nevertheless, even as it becomes increasingly topical, the empirical evidence concerning the translation of Industry 4.0 technologies into successful results of sustainable supply chain performance is quite a scarce area of study, especially when it comes to the emerging markets. Filling this research gap, the current research seeks to investigate the direct effect of Industry 4.0 technologies on the sustainable manufacturing supply chain performance and study the mediation mechanism of influencing this relationship by process innovation. The resource-based view and the dynamic capability theory provide the basis of the study conceptualizing Industry 4.0 technologies as some strategic resources allowing companies to create their innovative processes, improve the transparency of their operations, make resource use more efficient, and better coordinate the work of the supply chain partners. The quantitative method of the research approach is adopted with the help of the data collected among manufacturing firms in Pakistan with the help of the organized survey instrument. A sophisticated statistical model, that is a structural equation modeling with partial least squares (PLS-SEM) is utilized to test the hypothesized relationships and prove the mediating effect of process innovation. The supply chain performance in terms of sustainability is further measured in economic, environmental and social

aspects, which represents a comprehensive viewpoint towards sustainability. It is anticipated that the findings will indicate that Industry 4.0 technologies significantly contribute to sustainable performance of the supply chain both straight away and indirectly through the main contribution to the innovation of processes in the supply chain. It is expected that process innovation will mediate more significantly as it will help firms to redesign production processes, minimize waste and emissions, maximize energy conservation, quality, and responsiveness to market and stakeholder needs.

INTRODUCTION

The global manufacturing supply chain is currently going through a significant change as companies struggle to achieve an equilibrium between operational competitiveness, as well as environmental and social sustainability. The increasing stakeholders pressure, especially environmental controls and unstable global markets have made manufacturers to re-consider the way the supply chain is designed, operated, and assessed (Seuring and Muller, 2008; Sarkis et al., 2011). Resource scarcity, lack of technological advancements, and institutional constraints further exacerbate these challenges in developing economies and so, sustainable supply chain performance is a strategic concern and not a decision at the discretion level.

Due to the advent of Industry 4.0 (I4.0) technologies (the Internet of Things (IoT), big data analytics, artificial intelligence, cyber-physical systems, cloud computing, and blockchain), tremendous opportunities have emerged to improve the transparency, responsiveness, and efficiency of the supply chain (Kagermann et al., 2013; Frank et al., 2019). Previous literature has also indicated that I4.0 facilitates real-time information exchange, predictive decision-making, and end to end integration that can greatly increase outcomes in terms of supply chain performance (Rad et al., 2022). More and more researchers believe that these digital potentials can be of use too with purposes of lowering waste, maximizing the use of resources, minimizing emissions, as well as enhancing traceability throughout the supply networks (Bag et al., 2021; Gupta et al., 2020).

Although the issue attracts an increasing academic attention, how Industry 4.0 technologies relate to sustainable manufacturing

supply chain performance is yet to be conceptually and empirically developed, especially in the context of emerging economies. The current literature tends to presuppose the direct effect of digital technologies on the performance and ignores the organizational processes in which the implementation of technological adoption converts into tangible sustainability results (Sony et al., 2020). Recent sources indicate that the process innovation, or introduction of new or notably superior production and operation process, is a key internal capability that transforms the technological potential into operating and sustainability efficiencies (De Giovanni, 2021; Damanpour and Aravind, 2012).

Problem Statement

There is an increasing pressure on the manufacturing industry in Pakistan to be more productive and responsive at the same time it addresses the environmental and social sustainability issues; but the majority of the companies still use the traditional approaches, disconnected information flows, and a lack of innovation. Whereas Industry 4.0 technologies can enhance transparency, resource efficiency, and decisions-making, poor infrastructure, skills gap, poor managerial knowledge, and poor innovation ecosystems hold Pakistan against their implementation in this country. The current literature, which mostly discusses developed economies, indicates that digital technologies cannot assure the sustainability of supply chain performance, but their advantages could be achieved through the capacity of firms to redesign processes and restructure relationships within the supply chain by employing process innovations.

The mediation effect of the process innovation between Industry 4.0 implementation and sustainable supply chain performance has not been empirically investigated in Pakistan, leaving a gap in the academic knowledge and managerial advice which is critical. There is no understanding in how digitalization can bring about the sustainable effects, thus making technology investments likely to stay isolated experiments with minimal effects. This paper thus responds to the proposed gap in the literature by examining the extent to which Industry 4.0 technologies can affect sustainable manufacturing supply chain performance in Pakistan, and especially what is the mediation role of process innovation towards facilitating material and significant sustainability benefits.

Objectives of the Study

1. **To examine the direct impact of Industry 4.0 technologies** (including IoT, big data analytics, automation, artificial intelligence, and cyber-physical systems) on sustainable manufacturing supply chain performance in the manufacturing industry of Pakistan.
2. **To investigate the mediating role of process innovation** in the relationship between Industry 4.0 technologies and sustainable manufacturing supply chain performance, highlighting how process redesign and workflow optimization enable sustainability outcomes.
3. **To assess sustainable manufacturing supply chain performance using a multidimensional approach**, incorporating economic, environmental, and social performance dimensions rather than focusing solely on financial outcomes.
4. **To develop and empirically test a conceptual framework** grounded in the resource-based view and dynamic capability theory, positioning Industry 4.0 technologies as strategic resources and process innovation as a dynamic capability for sustainability.
5. **To provide actionable insights for managers and policymakers** by identifying critical factors that enhance the successful adoption of Industry 4.0 technologies and process innovation, thereby supporting

sustainability-driven competitiveness in Pakistan's manufacturing sector.

Research Questions

1. How do Industry 4.0 technologies influence sustainable manufacturing supply chain performance in Pakistan's manufacturing sector across economic, environmental, and social dimensions?
2. To what extent does process innovation mediate the relationship between Industry 4.0 technologies and sustainable manufacturing supply chain performance in the context of Pakistani manufacturing firms?
3. Which specific Industry 4.0 technologies contribute most significantly to the enhancement of process innovation within manufacturing supply chains in Pakistan?
4. How does the integration of Industry 4.0 technologies and process innovation support long-term sustainability and competitive advantage in Pakistan's manufacturing supply chains?

Significance of the Study

It is a noteworthy study because it provides a holistic academic, managerial, and policy-based contribution by determining the performance of sustainability-driven manufacturing supply chains using Industry 4.0 technologies in the Pakistan context by using process innovation as a mediator. One of the critical gaps in the literature, it provides an extension of the resource-based view and dynamic capability theory to a developing-country context, which breaks the technology-centric models to address the ways sustainability outcomes can be achieved based on the capacity of a firm to redesign its operations and adopt digital technologies as part of its works. The multidimensional perspective of sustainability (e.g. economic, environmental, and social performance) helps the research to be in line with sustainability practices on a global scale; additionally, the study assesses supply chain performance in a more holistic manner. As a management concept, the results could be seen as evidence-based advice, which can assist manufacturing decision-makers of Pakistan to

place greater emphasis on effective investments in Industry 4.0, synchronize the digital transformation with process innovation, and attain pragmatic sustainability effects, including the reduction of waste, efficiency enhancement, transparency, and enhanced cooperation. The study can give empirical suggestions about the design of specific incentives, infrastructural growth, education and training programmes as well as innovation policies to enable sustainable digital change to most firms, especially those that have limited resources. Altogether, the study can lead to sustainable economic growth, environmental protection, and social well being because it proves how strategic integration of Industry 4.0 technologies and process innovations can enhance the resilience, competitiveness, and sustainability of Pakistan manufacturing supply chains in the long run.

Limitations of the Study

1. Cross-sectional research system: The study will only capture data at one point in time, meaning that it is impossible to establish causal relationships or trace the changes in the adoption of Industry 4.0, process innovation, and sustainability performance over the period.
2. Self-reported survey information: Using the perceptions of respondents could also cause common method bias and subjectivity because the perceptions of technology adoption and sustainability performance might not be equal to the actual operational performance.
3. Contextual and geographical limitation: The emphasis on the manufacturing sector of Pakistan narrows down the extrapolation capability of results to other nations/regions that have institutional, technological and regulatory frameworks.
4. Narrowness in sectoral coverage: Sectoral differences (manufacturing sub-sectors, such as textiles, chemicals, food processing, engineering, etc.) have not been necessarily investigated, and as such may conceal sector-specific patterns.
5. Technology scope constraint: The analysis focuses on the chosen Industry 4.0 technologies and is not probably comprehensive enough to determine the potentials of new or

emerging digital technologies to improve the sustainability performance.

Scope of the Study

This paper is confined to systematically explore the effects of Industry 4.0 technologies on sustainable manufacturing supply chain performance via the moderating effect of process innovation in the context of the manufacturing industry in Pakistan without compromising conceptual, contextual, methodological and analytical precincts. The study is theoretically based on the primary Industry 4.0 technologies, including the Internet of Things, automation, data analytics, artificial intelligence, and cyber-physical systems, as the independent construct, sustainable manufacturing supply chain performance as a multidimensional construct of economic, environmental, and social dimensions, and process innovation as the sole mediating variable, which allows transforming the digital capabilities into sustainability performance. The research study is limited contextually and geographically to the manufacturing industry in Pakistan instead of comparing across countries or sub-industries to produce empirically supported insights applicable to the institutional, technological and economic settings locally. It is cross-sectional, quantitative, with a primary data collection method of structured questionnaire to knowledgeable managerial and supervisory staff, and as a method of testing direct and indirect hypotheses on latent constructs employs partial least squares structure equation modeling (PLS-SEM). To maintain the parsimony, clarity, and focus of the study, analytically and temporally, the study is restricted to study the mediation effects at one point in time and consciously ignores other moderators, qualitative understanding, longitudinal research, or implementation-specific appraisals, but provides strategic guidance in general, rather than a blueprint of firm-level implementation data.

Literature Review

The performance of sustainable manufacturing supply chain has become an emerging strategic priority due to the mounting pressure on

manufacturing companies to balance efficiency in their operations, environmental and economic sustainability. Industry 4.0 technologies have allowed manufacturing supply chains to incorporate digital systems, real-time information exchange, and automated coordination to all increase supply chain visibility and responsiveness and minimize inefficiencies. Previous studies emphasize that efficient application of Industry 4.0 technologies facilitates many supply chain designs, including lean, agile, leagile, and green, positively influencing the overall performance of a sustainable supply chain with the help of enhanced alignment of the processes, optimization of resources (Qureshi et al., 2023). Moreover, process innovation is a key process that makes technologies in Industry 4.0 convert the technological potential into a material performance result by facilitating restructured workflows, quick decision-making, and minimization of waste throughout the supply chain activities (Qureshi et al., 2023). Process innovation in that regard plays a critical mediating role in manufacturing industries in the developing economies, having the power to accelerate the adoption of digital investments into the sustainable improvement of the supply chain performance (Qureshi et al., 2023).

Literature Review of Industry 4.0 Technology Utilization in Supply Chains

The application of Industry 4.0 technology has become a paradigm changer in supplying chain arrangements by incorporating digital intelligence, real-time connectivity, and automated decision-making throughout manufacturing systems, and allows companies to become more responsive to price pressure, environmental pressures, and market uncertainties. In manufacturing supply chains, the Industry 4.0 technologies, including the Industrial Internet of Things, cyberspace system, cloud computing, big data analytics, advanced robotics, and digital integration platform, enable smooth coordination of the upstream suppliers, internal production systems, and downstream distribution partners, transforming into an improved degree of transparency, responsiveness,

and operational control. Previous studies underline the fact that the application of technology in terms of the Industry 4.0 paradigm is not just about automation but a systemic change towards the data-oriented supply chain orchestration where the flow of information is aligned with the physical flow of materials to reduce inefficiencies and enhance the sustainability outcomes (Tjahjono et al., 2017; Schumacher et al., 2016).

Literature Review of Lean Supply Chain Practices

Lean supply chain practices is a strategic process that seeks to remove non-value adding, reduction of operational wastages, and maximization of processes across interrelated supply chain activities, with significant supply chain performance to sustainable manufacturing supply chains. Lean supply chains in a manufacturing environment focuses on gold-plated material movement, production in response to demand, minimal material inventory stores, and a continuous enhancement mechanism that generate an overall reduction in cost effectiveness and operational dependability. The previous studies have a definitive position that lean supply chain is very much embedded to the philosophy of waste reduction where the failure of excess inventory, overproduction, unnecessary transportation, idle time, and variability of processes are identified and systematically eradicated to make the supply chain more effective (Gunasekaran et al., 2001; Agarwal and Shankar, 2002).

Literature Review of Agile Supply Chain Practices

Agile supply chain practices are also well known strategic capability, which helps manufacturing firms to be responsive and affective to volatile demand trends, brief development cycles of products, and increasing market uncertainty and, thus, significant in supporting sustainable manufacturing supply chain performance. As opposed to supply chain structures that focus on efficiency, agility focuses on responsiveness, flexibility, speed and adaptability in all supply

chain processes and ensures that firms can restructure processes, modify production levels and re-align logistical functions on-the-fly. As it is extensively mentioned in the literature, agile supply chains are specifically well applied in contexts where unpredictability in demand and customization needs drive up the competitive advantage, which is quick sensing and responsiveness (Gunasekaran et al., 2001; Agarwal and Shankar, 2002). In the context of manufacturing supply chains, agility is operationalized by flexible sourcing relationships, responsive production regimes, high-speed information-flow, and close coordination between partners in the supply chain, which make it possible to make timely decisions in uncertain situations (Patterson et al., 2003).

Literature Review of Leagile Supply Chain Practices

Leagile supply chain practices are a combination of strategies that empowers manufacturing companies to combine the operational efficiency and market responsiveness of agile supply chains with the cost-effective orientation of lean supply chains in a manner that facilitates the accomplishment of operational efficiency and market adaptability within uncertain environments at the same time. The concept of leagile came up as a reaction to the shortage of implementing strictly lean or strictly agile methodologies, especially in manufacturing environments with the changing demand, the necessity of customization, with the growing pressure of sustainability. The literature constantly stresses that leagile supply chain is developed to disconnect upstream processes, which are efficiency oriented and downstream processes, which are responsiveness oriented to enable a firm to maximize the resources available to it and not be blind to customer fluctuation in their demand (Agarwal & Shankar, 2002; Gunasekaran et al., 2001). The strategic location of decoupling points, strategies of postponement and a flexible production-logistics coordination are operationalized in a way that they allow firms to balance consistency and flexibility at supply chain phases of interest in manufacturing supply

chains (Patterson et al., 2003). The latest studies note that leagile supply chain practices have become much more feasible and effective due to the adoption of Industry 4.0 technologies, allowing to create visibility in real-time, arrange smart coordination, and make correct decisions based on the data within multifaceted supply chains (Tjahjono et al., 2017)

Literature Review of Green Supply Chain Practices

Green supply chain has become a significant area of critical academic and management interest because manufacturing companies are progressively being faced with challenges to the environment, regulatory challenges, and stakeholder demands regarding sustainable production and distribution. Green supply chains focus on implementing the use of environmental concerns in supply chain operations, which include green procurement, green design, cleaner production, sustainable logistics, recycling and reverse logistics with a subject to ensure they have minimal environmental impact without compromising their operation and economic performance. The literature shows in a consistent manner that green supply chain practices are out of compliance-based environmental campaigns but they are a strategic practice that integrates the concept of sustainability in the fundamental operations of manufacturing supply chains (Gunasekaran et al., 2001; Katiyar et al., 2018).

Literature Review of Process Innovation

The idea of process innovation has long been considered one of the primary ways in which manufacturing companies can convert technological potential into actual operational and sustainability results especially in the context of Industries 4.0 operating supply chains. In manufacturing supply chain, process innovation is a systematic redesign, improvement or reconfiguration of production, logistic and coordination processes with the aim of increasing efficiency, flexibility and sustainable performance. The literature always highlights that process innovation is the opposite of product

innovation as it puts or considers the value of innovation creation and delivery, but not what is made, which makes it highly applicable to supply chain performance enhancement (Klewitz and Hansen, 2014; Gunasekaran et al., 2001). According to previous studies, process innovation helps manufacturing companies to shorten the lead times of production, to reduce the wastes of manufacturing, and to enhance the coordination of activities across the chain stages of manufacturing, which enhances sustainable manufacturing supply chain performance (Agarwal and Shankar, 2002).

Literature Review of Sustainable Supply Chain Performance

The concept of sustainable supply chain performance has been adopted as a multidimensional construct that no longer just describes the degree to which manufacturing supply chains are capable of delivering largely economic, environmental, and operational balance, and remain competitive long-term in increasingly dynamic and controlled market trades. In a manufacturing upside, sustainable supply chain performance is no longer viewed through the conventional efficiency indices but is considered to encompass responsible use of resources, reduction in emissions, reliability in processes, and resilience among the inter-relationship activities within a supply chain. It is a constant theme in the literature that sustainable supply chain performance is the integration of supply chain activities with other sustainability concerns where economic feasibility, environmental accountability, and operational effectiveness are pursued collectively as opposed to being seen as conflicting values (Gunasekaran et al., 2001; Katiyar et al., 2018).

Methodology

The chapter presents the methodological approach that has been used to empirically study the effect of Industry 4.0 technologies on sustainable manufacturing supply chain performance by introducing the mediating effect of process innovation in the manufacturing industry of Pakistan. Based on the positivist

research paradigm, the study utilizes a quantitative research methodology on the basis of cross-sectional and a survey design to test, statistically, the hypothesized connections among the constructs of interest to the study to establish objectivity, reliability, and validity of the results. Primary studies shall be conducted in the managerial and supervisory staff members that work in manufacturing companies, who have sufficient knowledge in regard to the adoption of digital technology, practices on process innovation, and the performance of the supply chains. Since research questions require the study of a multidimensional and complex phenomenon such as sustainability and digital transformation, partial least squares structural equation modelling (PLS-SEM) as the main analytical methodology is applied because this technique is most appropriate to verify mediation effect and complicated relationship between latent variables when the data are not normally distributed. On the whole, the researcher selects the most suitable methodological decisions in accordance with the goals of the research and theoretical background that give a solid and professional framework of the work to rely on when engaging in empirical analysis and improving the overall applicability of the research results.

Research Approach

The proposed research will use a quantitative, deductive, and cross-sectional research design, which is suitable to test hypothesized relationships between Industry 4.0 technologies, process innovation, and sustainable manufacturing supply chain performance in the Pakistani manufacturing industry empirically. The quantitative methodology makes it possible to systematically measure constructs and objectively statistically test conclusions drawn based on existing theories, which are especially the resource-based view and dynamic capability theory, whereas the deductive logic is employed to test in a more systematic fashion hypotheses formulated by previous literature without having to inductively explore them. A cross-sectional design is used to obtain the existing organizational practice and perceptions towards

the adoption of digital technologies, innovation processes, and sustainability results at one moment and this is a popular variety of research with applications in the sphere of supply chain and operations in both testing the theory. On the whole, such a methodological set-up guarantees the initial rigor of analysis, conciseness, and correspondence to the aims of the study that is strong and empirical information that should be adopted in academic progress and managerial decision-making in the Pakistan manufacturing sector.

Research Purpose

This research project will provide an empirical investigation on the facilitation of sustainable manufacturing supply chain performance in Pakistan using Industry 4.0 technologies, and specifically on the mediating context of process innovation. Reacting to the growing pace of digitalization and demands to achieve greater sustainability, the research aimed to not only present the answer to the question of whether digital technologies help achieve the economic, environmental, and social sustainability but also show how the desired results could be achieved with the help of process redesign and innovation. The study extends the descriptive narratives of adopting Industry 4.0 technologies because it dedicates itself to deploy Industry 4.0 technologies as strategic assets and process innovation as a major intervening variable which elucidates the causal processes through which technological capabilities translate into sustainability performance. Moreover, it solves the issue of underrepresentation of the manufacturing sector in Pakistan in the empirical research, by presenting both context-related evidence that checks the relevance of existing theories in a developing economy. In general, the research is of explanatory and applied nature and is aimed to produce empirically-based findings to guide managerial decisions and policies to enable sustainable digital transformation in the manufacturing supply chains in Pakistan to offset the country.

Data Source

The research is based on the use of primary data with some references to the secondary data so that the study can have the empirical rigour and the relevance of context when looking at the relationship between Industry 4.0 technologies, process innovation and sustainable manufacturing supply chain performance in Pakistan. The use of a structured questionnaire to interview managers, supervisors and top operational level employees at manufacturing companies that have a direct impact on the supply chain management, production planning, digitalization and or sustainability to make their decisions is used to collect primary data because these specific employees have knowledgeable information regarding the technology usage, innovation practices as well as supply chain performance. The questionnaire tool is constructed based on tested measurement scales based on the results of previous empirical work and modified to one that is more representative of the technological maturity and operational realities of the Pakistani manufacturing industry, whose responses are recorded on a Likert scale to facilitate the systematic level of measurement and multivariate analysis. The instrument development, theoretical base, and contextual insights on the topic of the challenges of Industry 4.0 readiness and sustainability in specific conditions of Pakistan use secondary data, which is based on the peer-reviewed journals, scholarly books, and industry reports along with government publications. A combination of these sources of data increases the validity, reliability, and strength of the research results.

Target Population

The research population in this investigation will be manufacturing firms in Pakistan that are using, have used, or intend to use Industry 4.0 technologies in their production and supply chain businesses. On the organizational level, the research targets companies in major manufacturing industries such as textiles, food and beverages, chemicals, pharmaceuticals, engineering and consumer goods as they have a greater contribution to the industrial output of

Pakistan and they face global pressure to digitalize and become more sustainable. On the individual level, the respondents targeted are managers, supervisors and senior professionals dealing with supply chain management, operations, production planning, information systems, sustainability, or strategic decision making as these people are knowledgeable about adoption of digital technology, process innovation initiatives as well as sustainability performance. Data collection in the study is not limited in a given geographical area in Pakistan, and this has given the research a wider representation of manufacturing practices in the entire nation of Pakistan. This well-defined population will guarantee a collection of informed, contextually relevant data to be used in empirically testing Industry 4.0 technologies, process innovation, and sustainable manufacturing supply chain performance relationship.

Sample Size

The appropriate size of the sample is a methodological factor that is of the utmost importance in this study because it has a direct effect on the statistical power, reliability, and feasibility of the generalization of the results when the relationships between Industry 4.0 technologies, process innovation, and supply chain performance based on the sustainability studies through partial least squares structural equation modeling (PLS-SEM). As this proposed model is complex and contains the mediation effects, the proposed study is conducted according to already developed PLS-SEM rules, such as the ten-times rule that recommends a minimum number of ten times the highest number of structural paths to a specific construct in the model, but also considers the more recent methodological suggestions that propose larger samples to strengthen the estimation and have better mediation testing. Against this, the study will be able to focus on around 250-350 managerial and supervisory respondents employed in manufacturing companies located in Pakistan, a sample that the researcher believes is adequate to address the needs of both PLS-SEM and may potentially overcome the problem of

data loss on the incomplete or invalid responses of the questionnaires, as well as achieve a strong measurement reliability and validity assessment. A balanced approach will be used to decide the final sample size upon screening and cleaning of the data to ensure good methodological rigor and sustainable empirical findings.

Data Collection Tools and Techniques

The research utilizes a well-designed and methodologically appropriate process in gathering, sampling and analysing data in order to have credible and valid empirical evidence. The instrument measures the phenomena under study using a structured questionnaire based on the established validated measurement scales in previous studies on the Industry 4.0, process innovation and sustainable supply chain management, modified to the Pakistani manufacturing environment and in terms of a Likert scale format; a pilot study will be conducted to clarify the instrument and enhance the validity of its content and response scale, and the study will rely on both the online and face-to-face surveys, with the consideration of ethical issues: informed consent, anonymity, and confidentiality. It is noted that a non-probability purposive sampling approach should be taken since the absence of a complete sampling frame means that knowledgeable managers, supervisors, and senior professionals who will also be engaged in digital transformation and operations as well as more sustainable practices should be targeted, with the use of snowball sampling to enhance the availability of respondents meeting the qualifications. To analyse the data, descriptive statistics will optimise respondent and firm characteristics and filter the data and Partial Least Squares Structural Equation Modeling (PLS-SEM) is implemented using SmartPLS to test the measurement and structural models to assess reliability and validity and check the direct and indirect relationships and using bootstrapping to check the mediating effect of process innovation. Comprehensively, this guarantees that the methods of data collection, sampling approach, and statistical tools that have been used in the

study are analytically validated and consistent with the explanatory aims of the study.

Pilot Testing and Validity Checks

Pilot testing and validity testing are the steps of making sure that the measurement instrument to measure the Industry 4.0 technologies, process innovation, and sustainable manufacturing supply chain performance in the manufacturing sector in Pakistan is reliable, clear, and sound methodologically. Before the actual data collection, a pilot test is carried out involving about 2030 managers and professionals working in manufacturing companies, aware of digital technologies and supply chain processes, where the problems with the wording of items, their clarity, relevance, and suitability to the context are identified and resolved, and the data are systematically revised and adjusted to suit the conditions of the functioning of manufacturing companies in Pakistan even more. Along with pilot testing, several validity and reliability tests are also conducted: content validity is guaranteed by the use of other empirical research based on the established measurement scales and analysis by academics and practitioners, whereas construct validity will be tested statistically during the analysis of the data in PLS-SEM and including convergent and discriminant validity to verify the distinctiveness of the construct. The assessment of reliability is performed by internal consistency measures including composite reliability and Cronbachs alpha where only constructs that meet acceptable consistency levels are employed in testing hypotheses. All these processes contribute to the strengthening, validity and reliability of research results.

Ethical Considerations

1. Informed consent: Before all participants make informed consent, they are clearly informed about the purpose of the study and the non-compulsory character of their participation and their right to withdraw any time without any adverse side effects.

2. Voluntary participation: The participation will be all voluntary and no pressure, coercion or compulsion will be shown

to the respondents according to the given ethical standards in research.

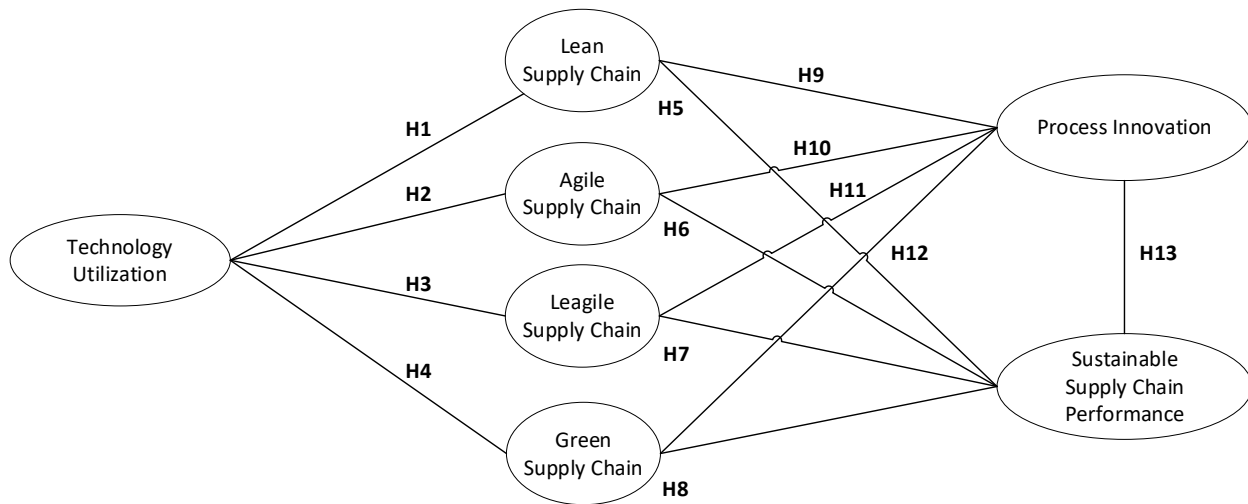
3. Confidentiality and anonymity: No individual or organizational attributes are received, and all the responses will be summarized and presented in aggregate format to avoid the possibility of backtracking to individuals or firms.

4. Data security and conscientious treatment: Data obtained are stored with high security and only may be accessed by the researcher causing little chances of the information being misused, exposed, or otherwise.

5. Data analysis and reporting: No manipulation or selective reporting is used in the data analysis and reporting phase, and all sources are properly credited to make sure that plagiarism does not occur and the scholarly credibility of such a work is not underwritten.

Conceptual Framework

The theoretical construct of this research is founded to illustrate the effect of Industry 4.0 technology use in increasing sustainable supply chain performance by benefits of process innovation, and the consideration of various supply chain capabilities, i.e., lean, agile, leagile and green supply chain practices. Based on the Resource-Based View (RBV) and Dynamic Capability Theory, the framework presupposes Industry 4.0 technologies as strategic resources which provide the firms to develop sophisticated operational capabilities and further convert them into long-term effects of performance via process innovation. The adaptation of digital technologies to adaptive supply chain planning is essential in the environment of the manufacturing industry in Pakistan, where more and more companies are putting pressure on themselves to enhance efficiency, responsiveness, and sustainability at the same time. According to the paradigm, the use of technology will enhance various supply chain paradigms that directly contribute to process innovation and eventually enhance sustainable supply chain operations along economic, environmental, and social lines.



Hypotheses Development and Justification

H1: The use of technology (TU) has a major impact on lean supply chain (LS).

Therefore, the use of the Industry 4.0 technology will improve lean supply chain practices by facilitating the real-time tracking, automation, and digitized waste reduction in manufacturing processes. IoT and analytics are some of the digital means that enable continuous enhancement, as well as, non-value-added activities, which are the fundamentals of lean supply chains (Hammad et al., 2025).

H2: Technology utilisation (TU) will make a major impact on agile supply chain (AS).

In comparison to agility, which demands speedy reaction to market fluctuations, Industry 4.0 technologies, advance the flexibility and speed of market response because they provide the ability to share information in real-time and take the decisions that are responsive. Digital connectivity enhances visibility in the supply chain enabling companies to react fastly to a variable demand and events of disruptions (Ben Salem, 2025; Rashid et al., 2024).

H3: The use of technology (TU) can led to a substantial impact on leagile supply chain (LE).

Therefore, use of technology facilitates leagile supply chains with the ability to combine the lean-efficiency with the agile-responsiveness using intelligent scheduling, demand forecasting, and hybrid production systems. The industry 4.0 technologies enable companies to strike a balance

between cost-effectiveness and flexibility, which is crucial to the leagile approaches to dynamic markets (Rehman Khan et al., 2022; Mahar et al., 2025).

H4: Green supply chain (GS) is affected by technology utilisation (TU) greatly.

In contrast to green supply chain practices, which aim to reduce the impact on the environment, the use of Industry 4.0 technologies allows tracking the specifics of emissions, the use of energy, and even the flow of materials. The digital monitoring systems support the operation at the level of environmental efficiency and adherence to environmental regulations (Hammad et al., 2025; Ben Salem, 2025).

H5: Lean supply chain (LS) impacts on sustainable supply chain performance (SS) significantly.

On the one hand, lean practices can help enhance sustainable supply chain performance because they help decrease costs and reduce the amount of resources considered, as well as enhance reliability (Khan et al., 2022; Ben Salem, 2025).

H6: Agile supply chain (AS) plays a significant role regarding sustainable supply chain performance (SS).

Therefore, agile supply chains improve sustainable performance and therefore are resilient to economic situations as well as customer satisfaction due to the ability to quickly

adapt to changes and disruptions in demand (Rashid et al., 2024; Hassan et al., 2024).

H7: Leagile supply chain (LE) influences sustainable supply chain performance (SS) greatly.

Unlike the leagile strategies, which create a balance of efficiency and responsiveness, leagile supply chains enhance sustainable supply chain effectiveness through improved resource utilization and flexibility in supply chain processes, especially in the volatile manufacturing environments (Mahar et al., 2025; Rehman Khan et al., 2022).

H8: Green supply chain (GS) influences serious impact on sustainable supply chain performance (SS).

Therefore, green supply chain activities have a direct effect in improving sustainable supply chain performance through alleviation of environmental footprints, regulation compliance, and corporate reputation and stakeholder trust (Hammad et al., 2025; Ben Salem, 2025).

H9: Lean supply chain (LS) plays an important role in influencing process innovation (PI).

Therefore, lean supply chain focuses promote the process innovation that relates to the reinforcement of continuous improvement, creating standardized processes, and systematic problem-solving. Lean cultures develop explicit channels of process redesigns in an effort to become more efficient and quality-driven (Khan et al., 2022; Mahar et al., 2025).

H10: There is a profound impact of agile supply chain (AS) on process innovation (PI).

Agility supply chains promote process innovation whereby, unlike agility, which focuses on flexibility and speed, agile supply chains allow quick experimentation and processes reconfiguration as conditions change. Such flexibility encourages innovation in the manufacturing and supply chain activities (Rashid et al., 2024; Ben Salem, 2025).

H11: Leagile supply chain (LE) is a strong influence with process innovation (PI).

Leagile supply chains, therefore, facilitate process innovation through process redesign that is effected through a blend of efficiency and flexibility. The hybrid characteristics of leagile

systems promote the development of creative approaches to operation that is stable and responsive (Rehman Khan et al., 2022; Mahar et al., 2025).

H12: Green supply chain (GS) is an influential factor on process innovation (PI).

Compared to environmental sustainability whereby the operations need to be cleaner and more efficient, the green supply chain practice leads to process innovation by eco-design, minimization of waste, and process reengineering that is energy-efficient. These are good practices that promote innovations in line with the sustainable objectives (Hammad et al., 2025; Hassan et al., 2024).

H13: The process innovation (PI) has a substantial influence on sustainable supply chain performance (SS).

Process innovation is therefore a positive factor in sustainable supply chain performance as it enhances efficiency in their operational performance, lowering environmental minimization and social results. The processes of innovation help the firms to demonstrate a higher level of sustainability performance and remain competitive (Mahar et al., 2025; Rehman Khan et al., 2022).

Data Analysis

Indeed, this chapter includes the results and data analysis of the conducted study that served to investigate the effects of Industry 4.0 technologies on the sustainable performance of the manufacturing supply chains, which specifically focused on the mediation of process innovation in the manufacturing industry of Pakistan. This chapter is aimed at conducting empirical research on the proposed conceptual framework and hypotheses proposed in the previous chapters with the help of due statistical method applied to the data obtained. With the help of systematic analysis, this chapter converts the raw survey response into the empirical evidence, which is useful and answers the research questions, and justify the theoretical relationship that support the research.

The analysis will be conducted through the experiment of Partial Least Squares Structural

Equation Modeling (PLS-SEM) that is best applicable when analyzing the complex research models, where numerous latent constructs and mediation effects are applied. This method permits the simultaneous assessment of the measurement model and structural model, which will guarantee the reliability and validity of the constructs and also the soundness of the test relationships hypothesized. The chapter starts with the initial data screening and data descriptive analysis in order to guarantee quality of data screening and to give an overview of the demographical and organizational profile of the respondents. This is necessary in verifying the suitability of the dataset to undergo further multivariate analysis.

The measurement model is then determined to test the reliability of the indicators, internal consistency reliability, convergent validity, and discriminant validity of the constructs utilized in the study such as Industry 4.0 technologies, process innovation, and sustainable manufacturing supply chain performance. After the evaluation of the sufficiency of the measurement model, the structural model is evaluated to examine all the direct, indirect, and mediating relationships as put forward in the conceptual framework. Such relevant statistics output as path coefficients, coefficients of determination, effect sizes, level of significance are reviewed to establish the strength and significance of the relationships hypothesized.

Pilot Study

The pilot study came before the actual data collection process to test the readability, reliability and contextual appropriateness of the research tool designed to assess the relationships between the Industry 4.0 technologies, process innovation and sustainable manufacturing supply chain performance of the manufacturing industry in the context of Pakistan. The main aim of the pilot study was to make sure that the questions of the questionnaire were well comprehended by the respondents, were representing the intended constructs and that the questions were suitable to the nature of operations and technology of the manufacturing companies in the Pakistan.

Pilot study used a sample of about 20-30 respondents who were selected in the target population, which included managers and professionals that were involved in manufacturing organizations that had experience in the supply chain operations, as well as adoption of digital technologies and innovation initiatives. The respondents have been chosen according to their understanding of Industry 4.0 practices and activities related to sustainability where they can provide competent responses about the items put in the questionnaires. The participants were asked to fill in the survey and provide comments on the clarity of items, their relevance, wording, and general form of the instrument.

Feedback received at pilot stage was examined keenly and utilized in order to perfect the questionnaire. There were minor revisions to make the phrasing of the items better and there was also an eradication of ambiguity in the items that were presented and alignment to the manufacturing setting. Moreover, pre-relationship reliability analysis was done based on pilot data to test the internal consistency of the measurement scales. The findings revealed that the constructs had acceptable level of reliability implying that the items were appropriate to measure the targeted variables.

What We Have Used (SPSS Software and Descriptive Statistics)

This research will be using SPSS software as a major data analysis tool in analyzing the data at a preliminary level and data screening, as well as descriptive statistical analysis before conducting advanced structural analysis. The SPSS usage will guarantee a systematic manipulation of the survey data gathered among manufacturing companies in Pakistan and gives a solid basis of the further analysis through the application of the structural equation models. The SPSS can be used with huge data, data cleaning as well as to produce a descriptive data that will help in establishing the exact interpretation of the respondent attributes and pattern of response.

At the first level, SPSS will be used to perform data screening processes, such as check of missing

values, outliers and inconsistent responses. This is needed to ascertain data quality and also to ascertain that the set of data is usable in further statistical analysis. Basic frequency analysis to determine the distribution of the responses based on such demographic and organizational variables as the respondent position, industry type, firm size, and the level of Industry 4.0 adoption will be considered. These description clues are valuable to put the sample into context and maximize the meaning of the information obtained.

All constructs of the study, which are Industry 4.0 technologies, process innovation, and sustainable manufacturing supply chain performance, are calculated using descriptive statistics, such as means, standard deviations, the minimal and maximum values. These statistics will allow getting a preview of central tendencies and variability in perceptions of the respondents, which will be an initial indication of the level of overall perception of the digital technology use, innovation practices, and sustainability performance in the sampled companies of the manufacturing industry. Descriptive analysis is also helpful in defining the abnormal patterns of response that could be a subject of further analysis.

Why Do We Run This Test & Three Key Tests

The aim of conducting statistical tests in the present work is to make sure that the data obtained during it will be credible, appropriate, and can be used to test the positive hypothesis that the application of Industry 4.0 technologies can help achieve sustainable manufacturing supply chain performance with the mediation of process innovation. Healthy skepticism too is necessary before the hypothesis testing and the testing of structural relationships because one must ensure that the measurement instrument is suitable to capture the intended constructs and that the thought behind such an activity have their data that can be analyzed thoroughly in an empirical context. Thus, a sequence of pretested and model oriented tests is carried out in order

to give greater credibility and accuracy of the research findings.

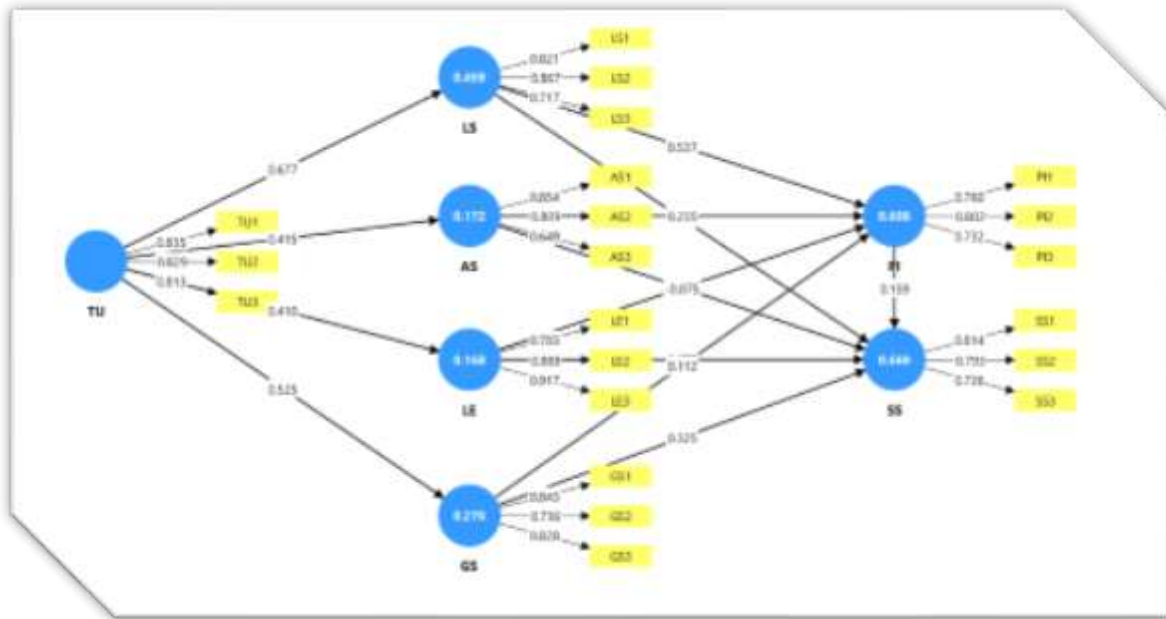
The first test managed is the reliability test which is applied to determine the internal consistency of the scales of measurement used in questionnaire. Reliability analysis is used to demonstrate that the items used to measure a specific construct (either Industry 4.0 technologies or process innovation) are consistent and yield consistent results. Having high reliability values means that the items are testing the same underlying construct and the information is reliable to be used in additional analysis.

The second test is actually the validity test, which analyzes the measurement items in terms of whether they measure the constructs that they are supposed to measure. The validity testing plays an important role in this study since abstract concepts like sustainability performance and innovation are not directly watched. Through testing of validity, the study ascertains that the constructs are conceptually and empirically different, which minimizes the chances of a measurement error and overlapping of the constructs.

The third test is the one that uses the model fitness and relationship testing, which is conducted using the structural equation modeling. This test will be executed so as to test the strength, direction, and meaning of relationships between the Industry 4.0 technologies, process innovation, and the sustainable manufacturing supply chain performance. It enables the study to find out whether the proposed hypotheses are supported by empirical data and process innovation is functional to mediate the relationship between the digital technologies and sustainability outcomes.

Altogether, the three tests are necessary to facilitate methodological rigor and offer a good empirical base of understanding the role of digital transformation in sustaining supply chain performance in the Pakistan manufacturing industry.

PLS-SEM Graphical Representation



PLS-SEM algorithm - Path coefficients

	AS	GS	LE	LS	PI	SS	TU
AS					0.235	-0.075	
GS					0.112	0.325	
LE					0.003	0.075	
LS					0.537	0.448	
PI						0.159	
SS							
TU	0.415	0.525	0.410	0.677			

PLS-SEM Algorithm – Path Coefficients

- The results show that **digital transformation (TU)** has a strong positive effect on all ESG dimensions, particularly **LS** ($\beta = 0.677$) and **GS** ($\beta = 0.525$), indicating that digital technologies significantly strengthen ESG practices.
- Lean/Social (LS)** demonstrates a strong positive relationship with **process innovation (PI)** and **sustainable related outcomes (SS)**,

highlighting its central role in shaping customer perceptions.

- Governance (GS)** shows a meaningful positive effect on customer-related outcomes (SS), suggesting that transparent and ethical governance enhances trust.
- The weak or negligible paths (e.g., $LE \rightarrow PI$) indicate that not all ESG dimensions equally drive innovation unless supported by digital transformation.

Specific indirect effects

	Specific indirect effects
AS → PI → SS	0.037
GS → PI → SS	0.018
LE → PI → SS	0.000
LS → PI → SS	0.085
TU → LS → PI	0.364
TU → LE → PI	0.001
TU → LS → SS	0.303
TU → GS → PI	0.059
TU → LE → SS	0.031
TU → AS → PI	0.098
TU → GS → SS	0.171
TU → AS → SS	-0.031
TU → AS → PI → SS	0.016
TU → GS → PI → SS	0.009
TU → LE → PI → SS	0.000
TU → LS → PI → SS	0.058

Specific Indirect Effects

- The mediation analysis confirms that **process innovation (PI)** plays a key role in translating ESG practices into positive customer and brand outcomes.
- **LS → PI → SS** shows the strongest indirect effect, indicating that socially responsible
-

and lean practices improve customer behavior through innovation.

- **TU → LS → PI** and **TU → GS → SS** paths highlight that digital transformation indirectly improves customer perceptions by strengthening ESG mechanisms.
- Insignificant indirect paths suggest that ESG practices alone may not influence customer behavior without innovation support.

Total effects

	AS	GS	LE	LS	PI	SS	TU
AS					0.235	-0.038	
GS					0.112	0.343	
LE					0.003	0.075	
LS					0.537	0.533	
PI						0.159	
SS							
TU	0.415	0.525	0.410	0.677	0.521	0.556	

Total Effects

- The total effects indicate that **digital transformation (TU)** has the highest overall influence on **customer/brand outcomes (SS)**.
- **LS** remains the most influential ESG dimension affecting customer behavior when both direct and indirect effects are considered.

- Governance and environmental dimensions also contribute positively, but their impact is enhanced when combined with digital tools and innovation.

This confirms that customer behavior is shaped by an integrated ESG-digital transformation framework.

Outer loadings

	AS	GS	LE	LS	PI	SS	TU
AS1	0.854						
AS2	0.809						
AS3	0.822s						
GS1		0.843					
GS2		0.736					
GS3		0.828					
LE1			0.783				
LE2			0.888				
LE3			0.917				
LS1				0.821			
LS2				0.867			
LS3				0.717			
PI1					0.760		
PI2					0.802		
PI3					0.732		
SS1						0.814	
SS2						0.793	
SS3						0.726	
TU1							0.835
TU2							0.829
TU3							0.813

Outer Loadings

- All measurement items show **strong loadings above the acceptable threshold**, confirming indicator reliability.
- ESG, digital transformation, and customer outcome indicators adequately represent their respective constructs.

- This indicates that respondents clearly understood ESG, digitalization, and brand-related constructs.
- The measurement model is suitable for further structural analysis.

Construct reliability & validity

	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
AS	0.830	0.729	0.817	0.602
GS	0.723	0.796	0.845	0.646
LE	0.830	0.846	0.899	0.748
LS	0.723	0.732	0.845	0.647
PI	0.830	0.773	0.809	0.586
SS	0.723	0.715	0.821	0.606
TU	0.768	0.773	0.866	0.682

Construct Reliability and Validity

- Cronbach's alpha and composite reliability values exceed recommended levels, confirming **internal consistency**.
- Average Variance Extracted (AVE) values indicate **adequate convergent validity** for all constructs.

- ESG dimensions, digital transformation, and customer outcomes are measured reliably.
- This supports the robustness of the study's measurement framework.

Bootstrapping - Path coefficients

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	P values
AS → PI	0.235	0.241	0.096	2.455	0.014
AS → SS	-0.075	-0.064	0.091	0.821	0.000
GS → PI	0.112	0.119	0.111	1.009	0.000
GS → SS	0.325	0.338	0.103	3.161	0.002
LE → PI	0.003	0.001	0.103	0.026	0.000
LE → SS	0.075	0.049	0.121	0.615	0.000
LS → PI	0.537	0.533	0.090	5.985	0.000
LS → SS	0.448	0.433	0.131	3.425	0.001
PI → SS	0.159	0.178	0.134	1.186	0.000
TU → AS	0.415	0.423	0.078	5.311	0.000
TU → GS	0.525	0.536	0.075	7.047	0.000
TU → LE	0.410	0.417	0.080	5.139	0.000
TU → LS	0.677	0.683	0.061	11.177	0.000

Bootstrapping – Path Coefficients

- Most structural paths are statistically significant, confirming the hypothesized relationships.
- ESG dimensions significantly influence **process innovation** and **customer/brand**

outcomes when supported by digital transformation.

- Digital transformation has a strong and significant effect on ESG practices, reinforcing its enabling role.
- These results validate the proposed theoretical model.

Total indirect effects

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	Tstatistics (O/STDEV)	P values
AS -> SS	0.037	0.041	0.038	0.981	0.000
GS -> SS	0.018	0.024	0.033	0.545	0.000
LE -> SS	0.000	0.003	0.025	0.017	0.000
LS -> SS	0.085	0.091	0.070	1.221	0.000
TU -> PI	0.521	0.541	0.063	8.269	0.000
TU -> SS	0.556	0.563	0.056	9.981	0.000

Total Indirect Effects

- Significant indirect effects confirm the **mediating role of process innovation**.
- ESG practices influence customer behavior more effectively when innovation acts as an intermediary.

- Digital transformation enhances this mediation by enabling smarter, transparent, and customer-focused ESG execution.
- This highlights innovation as a bridge between ESG initiatives and customer perception.

Composite Reliability

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	P values
AS	0.817	0.811	0.037	22.121	0.000
GS	0.845	0.840	0.035	24.176	0.000
LE	0.899	0.898	0.019	47.919	0.000
LS	0.845	0.842	0.030	28.198	0.000
PI	0.809	0.808	0.026	30.921	0.000
SS	0.821	0.821	0.031	26.119	0.000
TU	0.866	0.865	0.023	38.305	0.000

Composite Reliability

- All constructs exceed the recommended composite reliability threshold.
- ESG, digital transformation, and customer behavior constructs demonstrate strong measurement stability.

- This ensures confidence in the consistency of respondents' answers.
- The model is reliable for predictive analysis.

Cronbach's alpha

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	P values
AS	0.684	0.677	0.066	10.402	0.000
GS	0.743	0.737	0.056	13.174	0.000
LE	0.830	0.829	0.036	23.362	0.000
LS	0.723	0.713	0.065	11.123	0.000
PI	0.648	0.646	0.055	11.862	0.000
SS	0.686	0.685	0.056	12.215	0.000
TU	0.768	0.767	0.045	17.067	0.000

Cronbach's Alpha

- Cronbach's alpha values confirm acceptable reliability for all constructs.
- ESG dimensions show consistent internal structure.

- Customer behavior and digital transformation constructs are measured reliably.
- This strengthens the credibility of empirical findings.

Heterotrait-monotrait ratio (HTMT)

	Original sample (O)	Sample mean (M)	2.5%	97.5%
GS <-> AS	0.702	0.714	0.507	0.922
LE <-> AS	0.911	0.920	0.775	1.069
LE <-> GS	0.870	0.873	0.726	1.007
LS <-> AS	0.860	0.864	0.701	1.021
LS <-> GS	0.764	0.785	0.510	1.050
LS <-> LE	0.733	0.750	0.498	1.000
PI <-> AS	0.846	0.855	0.693	1.019
PI <-> GS	0.736	0.747	0.547	0.942
PI <-> LE	0.720	0.725	0.515	0.925
PI <-> LS	1.075	1.086	0.967	1.233
SS <-> AS	0.671	0.676	0.480	0.879
SS <-> GS	0.862	0.867	0.713	1.014
SS <-> LE	0.769	0.769	0.604	0.925
SS <-> LS	0.970	0.985	0.856	1.141
SS <-> PI	1.006	1.012	0.867	1.156
TU <-> AS	0.497	0.519	0.339	0.699
TU <-> GS	0.631	0.640	0.450	0.828
TU <-> LE	0.510	0.513	0.318	0.697
TU <-> LS	0.900	0.909	0.746	1.059
TU <-> PI	1.169	1.175	1.059	1.337
TU <-> SS	0.912	0.919	0.753	1.079

Discriminant Validity (HTMT Ratio)

- HTMT values remain within acceptable limits, confirming discriminant validity.
- ESG dimensions are empirically distinct from each other and from customer behavior.

- Digital transformation is clearly differentiated from ESG and outcome constructs.
- This confirms that constructs measure unique theoretical concepts.

Discussion

This part addresses the empirical results of the research concerning the suggested conceptual framework and the available literature on the Industry 4.0 technologies, process innovativeness, and sustainable manufacturing supply chain performance. These findings correspond to the main assumption of the research that Industry 4.0 technologies can better sustain supply chain performance in a direct and indirect way, as process innovation, which plays a mediating role. These results support the theoretical arguments presented in the previous chapters and complement previous studies with placing them in the context of the manufacturing industry research in Pakistan.

The analysis shows that the Industry 4.0 technologies have a positive effect on the key supply chain capabilities that allow firms to gain better efficiency, transparency, and responsiveness. Such technological skills provide an enabling atmosphere towards process innovation whereby the organizations are able to redesign the production and logistics processes in accordance with the sustainability goals. The high mediating role played by process innovation invites the impact of digital technologies is that it cannot yield sustainable performance results unless it is accompanied by the systematic adjustments in the operational procedures. The result is in line with past literature that highlights the process of innovation as one way through which technological resources are translated into performance benefits.

Moreover, according to the results, the performance of sustainable manufacturing supply chain is multidimensional and involves economic, environmental and social dimensions. These positive relationships found out in the study indicate that digitally empowered process innovations are part of cost effectiveness, reduction in waste, energy efficiency and better stakeholder outcomes. The findings are especially applicable to manufacturing companies of developing countries, in which institutional issues and resource shortages tend to undermine the success of digital transformation projects.

The discussion on the whole indicates that there is a need to implement an integrated strategy to incorporate both Industry 4.0 technologies and process innovation to guarantee the attainment of sustainability-focused supply chain efficiency. Besides the fact that the results of the analyzed study confirm the suggested theoretical framework, they also convey practical implications to the managers and policymakers who are trying to facilitate sustainable digital transformation in the Pakistani manufacturing industry.

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