



Driving Success through Digital Transformation: Influence of Industry 4.0 on Lean, Agile, Resilient, Green Supply Chain Practices in Pharmaceutical Sector of Karachi, Pakistan

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ABSTRACT

The present study seeks to examine the impacts of Industry 4.0 (I4.0) tools Blockchain, Internet of Things (IoT), Machine Learning (ML), and Data Analytics (DA) on lean, agile, resilient, and green (LARG) supply chain practices and consequently operational performance measures, which are cost and customer service performance, in the pharmaceutical industry in Karachi, Pakistan. A quantitative study methodology was employed to collect data on 207 valid responses collected under the purposive sampling technique using a structured survey to be administered to senior operational and supply chain employees at leading pharmaceutical firms in Karachi. Both direct and indirect effects were analyzed using PLS-SEM or the partial least squares structural equation modeling. The results imply that the operation of LARG supply chain with the use of I4.0 technologies is significantly enhanced by blockchain and data analytics. LARG methods greatly affect both the cost performance and the customer service performance. The mediation analysis shows that the relationship between I4.0 tools and performance outcome falls under the LARG paradigms partially, which indicates that the performance benefits of digital transformation are achieved through changes in operational processes. These findings go in line with the theoretical assertion that digital change transforms the pharmaceutical supply chains to be competitive, flexible, resilient, and sustainable. The current study provides one of the earliest empirical studies relating I4.0 tools to dual performance results and LARG supply chain practices that are involved in the pharmaceutical industry of Pakistan. It develops theory by integrating the LARG and the digital transformation paradigm into one. It also contributes to practice by giving industry-specific data of an upcoming economy that is regulated and is likely to be disrupted.

Introduction

High-tech solutions such as cyber-physical systems, artificial intelligence (AI), big data solutions, machine learning, robotics, blockchain, and the Internet of Things (IoT) are significantly pushing the global corporate environment to a fast digitalization. The Industry 4.0 (I4.0) is a technological revolution that transforms the supply chain systems and traditional industry operations (Fettermann et al., 2018; Raut et al., 2020.) The digital solutions offer visibility, automation, real-time monitoring, and integrated decision-making in supply chain management (SCM) (Oliveira and Handfield, 2019; Al-Khatib, 2023).

Some of the challenges that the pharmaceutical industry encounters, particularly in the developing world such as Pakistan, include regulatory pressures, instability in supply channels, sustainability demands, and disruptions in supply networks in the global market. Organizations are actively applying Lean, Agile, Resilient, and Green (LARG) supply chain practices to focus on these issues and stay competitive in the long term and operations excellence (Carvalho et al., 2011; Azevedo et al., 2013).

Digital transformation includes redesigning and optimization of supply chain processes by applying Industry 4.0 technology. These technologies enhance accuracy of forecasting, reactivity, visibility and integration (Frederico et al., 2021; Dalmarco et al., 2019) Studies show that IOT, cloud solutions, AI, and data analytics significantly enhance predictive insights, collaborative planning and decision-making (Tao et al., 2018; Dubey et al., 2018). The application of I4.0 is necessary to achieve flexibility, operational efficiency, resilience, and sustainability in highly dynamic circumstances (Marcucci et al., 2022; Umar et al., 2022).

LARG Supply Chain Model Development

The LARG framework contains four strategies of supply chains.

Lean decreases waste and enhances effectiveness of processes (Chavez et al., 2013; Sajan et al., 2017).

Agile insists on flexibility to changes in the market (Gligor et al., 2019; Oliveira-Dias et al., 2022).

Resilient means the ability of the supply chain to predict, withstand and recover due to disruptions (Carvalho et al., 2012; Dubey et al., 2021).

Green fosters eco-efficiency and environmental sustainability (Jaggernath and Khan, 2015; Balon, 2020) Academics state that a combination of the four paradigms will create a comprehensive framework of effective and sustainable supply chain performance (Govindan et al., 2015; Silvestre et al., 2020)

The Assistance of LARG Capabilities via Industry 4.0.

The recent research has shown that Industry 4.0 technologies directly enhance LARG procedures. Indicatively, (Khanchanapong et al. (2014) and Kamble et al. (2020)) IoT and cloud capabilities are useful in lean operations by reducing waste. Digital twins, blockchain, and predictive analytics can improve agility (Tarafdar and Qrunfleh, 2017) When reducing emissions and encouraging circular transformations, artificial intelligence and big data analytics improve green outcomes (Antikainen et al., 2018; Dev et al., 2020). Consequently, I4.0 is a strategic mobilizer to facilitate integrated LARG performance.

Pharmaceutical Supply Chain in the Karachi, Pakistan

All Karachi is the main manufacturing centre of pharmaceuticals and most of the production, warehousing and distribution activities are in this city. The contribution of the Industry 4.0 technologies to LARG skills in Karachi remains an under-researched phenomenon, even though the pace of the digital transformation is increasing. As of 2025, there have been 650 to 700 registered pharmaceutical businesses (both local and foreign) operating all over Pakistan.

Statement of the Problem

The pharmaceutical industry of Pakistan (particularly Karachi) has had considerable structural and operational constraints in the recent years. Although retail sales of the national pharmaceutical market grew in 2025 to more than PKR 1.049 trillion, the real unit growth stood at 3.63% only, which indicates that the national pharmaceutical market is not accompanied by productivity or operational efficiency among its operations, but rather by price increases (Profit by Pakistan Today, 2025; IQVIA, 2025). The growing divergence between growth of value and volume highlights necessity of supply-chain operations that are cost-efficient, adaptable, resilient and environmentally friendly. The industry is however, highly concentrated with 87 organizations owning 96.5 percent of the market value. This exerts pressure to the local and mid-sized businesses aiming to enhance the reliability of services, reduce wastage, and maximize performance (The News International, 2025).

Objective of the Study

In order to evaluate the Direct variables of Cost Performance and Customer Service Performance (CP,CSP) by evaluating the Mediating roles of Lean, Agile, Resilience, and Green (LARG) practices in pharmaceutical supply chains in Karachi, and the impacts of the Indirect variables of Industry 4.0 technologies Internet Of Things, Machine Learning, Blockchain and Data Analytics (IOT,ML,BC,DA).

1. To assess the utilization of IOT, ML, BC and DA in the pharmaceutical supply chains of Karachi.
2. To examine the direct effect of IOT, ML, BC and DA on cost performance.
3. To examine the direct effect of IOT, ML, BC and DA on cost-service performance.
4. To find out the influence of IOT, ML, BC and DA on the Lean methodologies.
5. To ascertain the effects of IOT, ML, BC and DA on Agile methodologies.
6. To establish the influence of IOT, ML, BC and DA on supply chain resilience practices.
7. To ascertain the influence of ML, DA, BC and IOT on green practices.
8. To quantify the impact of LARG methods on the cost performance and customer service performance.
9. To research the resilient practices mediating the relationship between the supply chain performance outcomes and the Industry 4.0 adoption.
10. To test the extent to which the green practices mediate the adoption of Industry 4.0 and the results of supply chain performance.
11. To provide useful recommendations as well as empirical evidence on how to improve the performance of the service levels, cost effectiveness, and operational efficiency of the Karachi based pharmaceutical supply chains.

Research Questions

1. How does the adoption of Industry 4.0 affect the supply chain strategies of Lean, Agile, Resilient, and Green (LARG) in Karachi pharmaceutical companies?

2. To what extent does Industry 4.0 implementation have direct effects on the customer service and cost performance?
3. Does LARG play the role of a mediator in the association between supply-chain performance (cost performance and customer service performance) and Industry 4.0 adoption?

Literature Review

Theoretical Underpinning

The available literature underlines the value of dynamic capability when implementing lean, agile, and resilient supply chain strategies (Dubey et al., 2018) and a natural resource-based view of the green supply chain efforts (Balon, 2020). Nonetheless, a business requires a large scale approach in order to ensure high performance. The systems theory can assist in implementing lean, agile, resilient, and sustainable supply chain methods. As an academic origin, it addresses the issue of complex interdependencies and interconnections in the supply chains and describes the systems as related elements that are organized to achieve specific objectives (Puche et al., 2016). Choi et al. (2019) note that the holistic approach has features and synergies that transcend traditional constraints. Sajan et al. (2017) propose the systems theory as an advocate of lean techniques, which looks at the sources of waste in the system. Khan et al. (2022) assert that the nimble approach to supply chain management is flexible and aligns with the dynamic nature of the latter. The resilient supply chains should understand the hazards and interdependencies observed in the complex adaptive systems (Piprani et al., 2023). Finally, but not the least, the system-wide strategy includes the sustainability programs aimed at minimizing the environmental impact (Shah et al., 2023).

Hypothesis Development

Industry 4.0 and SCP technologies

Industry 4.0 involves the implementation of cloud computing, big data analytics, cyber-physical systems, and interconnected digital infrastructures to logistics and industrial systems (Dalmarco et al., 2019). Empirical research shows that better supply chain visibility, coordination, and accuracy in decision-making are usually found in companies utilizing I4.0 (Al-Khatib, 2023; Dubey et al., 2021). These features enhance the customer response and efficiency of the operation, two fundamental customer performance of the supply chain (Wamba et al., 2017).

Industry 4.0 consists of blockchain, IoT, ML, and DA to enhance functioning and restructure supply chains through sharing real-time data (Santos et al., 2023). The technologies have been selected due to their ability to offer a comprehensive, cost-effective technology package and suitability with the needs of manufacturing in Pakistan and its readiness to begin the Fourth Industrial Revolution. IoT enhances real-time tracking and operational efficacy, ML enhances decision-making and process efficacy, analytics enhance productivity and customer support, and blockchain ensures secure and transparent data sharing (Wamba et al., 2017, Khan et al., 2021a, b). When integrated, these I4.0 technologies can make work in companies easier, enhance the balance between supply and demand, increase productivity, and reduce costs and production durations (Al-Khatib, 2023). As a result, it can be concluded that

H1. The positive and significant effects of the I4.0 tools usage on SCP are positive and significant.

Industry 4.0 and LARG

Lean supply chain methods emphasize heavy focus on the removal of waste, enhancement of processes and minimization of buffering to enhance flow and cost effectiveness. The technologies of I4.0 can be used to achieve the lean objectives providing better workflow visibility, automated monitoring, real-time, and predictive analytics (Kamble et al., 2020). As an example, pharmaceutical companies can optimize production batches, can remove loss related to deviations, and can also reduce documentation rework with the help of advanced analytics. Although Getz Pharma in Pakistan has adopted integrated ERP systems to reduce the variability in the processes and improve GMP compliance, multinational companies such as Novartis have used machine learning as a predictive maintenance tool.

Industry 4.0 and LSCP

I4.0 assists industrial firms to deal with lean implementation challenges. Researchers have examined the role of various I4.0 tools in enhancing the working of the lean supply chain (LSCP). I4.0 real-time information also allows planning the value chain processes and identifying issues (Kamble et al., 2020). Changeover times are reduced through timely communication, and just-in-time efficiency is enhanced through the use of electronic product identification. Also, such real-time information enhances the program such as Kaizen, process visibility, and product quality (Oliveira and Handfield, 2019). As a result, it is thought that

H2a. The positive relationship exists between I4.0 Technologies and LSCP.

Industry 4.0 and ASCP

Agile supply chain practices promote rapid flexibility and responsiveness to the fluctuating market environment. Examples of I4.0 technologies that can assist businesses in predicting changes in demand and swiftly responding to supply capabilities include predictive analytics, cloud coordination, and IoT (Oliveira-Dias et al., 2022). The pandemic disruptions in the pharmaceutical companies were flexible as the firms shifted production to high-demand drugs and vaccinations.

H2b: There is a positive relationship between I4.0 technologies and ASCP.

Industry 4.0 and RSCP

The ability of supply chains to persist amidst disruptions and recover performance is known as resilience. Pharmaceutical supply hazards are cold-chain failures, customs veto, and APIs importation. The technologies of I4.0 can be employed to increase resilience by using blockchain authentication, risk analytics, multi-tier visibility, and digital traceability (Brusset and Teller, 2017; Qader et al., 2022). As an example, Searle has been strategic in terms of supplier diversification and the use of automated planning in order to deal with the API shortage whereas Pfizer has adopted digital serialization to prevent counterfeiting.

H2c. The relationship between I4.0 Technologies and RSCP is positive.

Industry 4.0 and GSCP

Green practices address matters that have environmental impacts like waste materials, emissions, disposal of hazardous materials. Pharmaceutical industries should comply with environmental regulations as they produce extensive packaging and chemicals waste. I4.0 also facilitates green activities through the use of digital monitoring, material optimization, and energy control (Antikainen et al., 2018; Ghadge et al., 2022). Getz Pharma has global environmental certification

to be able to continue the export market, whereas Johnson and Johnson and Bayer report about the reduction of emissions using clever manufacturing technologies.

H2d. GSCP has positive correlation with I4.0 Technologies.

LARG and SCP

Chavez et al. (2013) observe that LSCP enhances quality and efficiency through wastes reduction. Agile strategies are flexible and responsive to their customers. To make sure that the products meet the expectations of clients, ASCP lays a high stress on the ability to adapt to changing markets and demands (Tarafdar and Qrunfleh, 2017). RSCP minimizes downtime and accelerates recovery and increases resilience in case of unplanned situations (Piprani et al., 2021). To achieve sustainability in the future, GSCP incorporates sustainability into operational efficiency, paying close attention to environmentally friendly practices (Khan et al., 2022a). These strategies are complementary, as they increase the sustainability, risk management, responsiveness, and efficiency of the supply chain. LARG principles result in significant performance gains since delivery, quality, flexibility, cost-effectiveness, and competitiveness are all greatly enhanced. Lean approaches have been shown to improve SCP through the reduction of inventory prices, reduction of lead times, and elimination of waste in operations (Chavez et al., 2013). So

H3a. SCP is also positively correlated to LSCP.

Tarafdar and Qrunfleh (2017) state that agility enhances SCP by improving the reliability of fulfillment, product availability, and responsiveness to pharmacies and medical workers. Thus,

H3b. There is a positive relationship between ASCP and SCP.

Hamidu et al. (2023) state that resilience assists SCP in reducing the cost of interruption, improving continuity, and stabilizing delivery lead times. Thus,

H3c. There is a positive correlation between RSCP and SCP.

Green practices enhance regulatory acceptance and client trust (customer service performance) and reduce waste disposal expenses (cost performance) that both facilitate SCP (Umar et al., 2022). Consequently

H3d. GSCP has a positive relationship with SCP.

Mediating effect of LARG

Previous studies indicate that I4.0 technologies can hardly directly translate performance results, unless they are integrated operationally in the supply chain routines (Raut et al., 2021). LARG methods re-codify the digital capabilities into digital results that are sustainable, responsive, efficient, and continuous. The I4.0 technologies could significantly improve supply chain performance, provided that they are used as a part of a bigger strategy. The enhancement of LARG approaches include a holistic approach that ensures the full benefits of I4.0 through the integration of different technologies to share information, coordinate, and make analytics. To make supply chains more resilient, efficient, responsive, and sustainable, it is necessary to have an integrated LARG approach. As a result, the hypothesis below is formulated (see Figure 1).

Hence, it is expected that LARG procedures will moderate the relationship between I4.0 and SCP:

H4a. LSCP are used to mediate between I4.0 tools and SCP.

H4b. ASCP are in between I4.0 tools and SCP.

H4c. RSCP are used to mediate between I4.0 tools and SCP.

H4d. GSCP establish the linkage between I4.0 tools and SCP.

Research Methodology

Research Design

Instrument Development

This study is a survey comprised of pre-determined questionnaires comprised of studied constructs and demographics. These four facets of the I4.0 technological architecture are IoT, blockchain, and machine learning (ML), which is inspired by Qader et al. (2022), SCDA, which can be assessed by five various metrics based on Khan and associates, 2022b. The LARG paradigm consists of LSCP (Khan et al., 2021b), ASCP (Dubey et al., 2018), RSCP (Gölgöçü and Ponomarev, 2015), and GSCP. The two dimensions of SCP are cost effectiveness and customer service performance, which are borrowed as per Um et al. (2017). On each statement Likert scale of seven points grading is applicable where strongly agree (7) and strongly disagree (1) are the two extremes.

Sampling

This paper used cross sectional survey as its methodology in the pharmaceutical industry in Karachi, Pakistan. In order to achieve the research goal, to follow a certain population with a certain constraints regarding time, resources and the peculiar features of our target group, we selected the convenience sampling as the effective method of gathering information in an efficient way. We have approached the WhatsApp and LinkedIn of experienced supply chain professionals of Searle Pakistan Limited company and Getz Pharma. Firstly we got 87 responses, and there were 52 more responses following a follow up message. Using a key informant methodology, we filtered out irrelevant job title, and ended up with the final sample of top, middle and lower level management positions. Our survey online received 68 responses giving it a total of 207 valid responses.

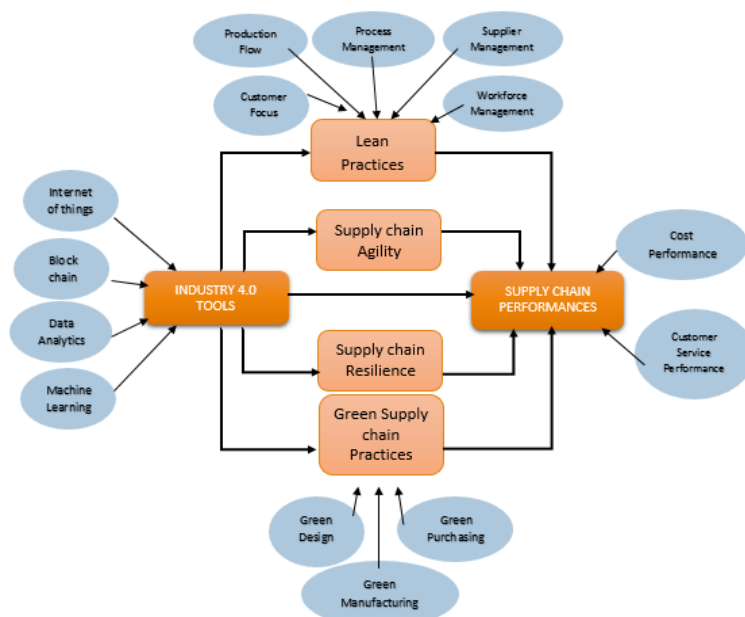


Figure 1 Conceptual Framework

Results and Discussion

PLS SEM

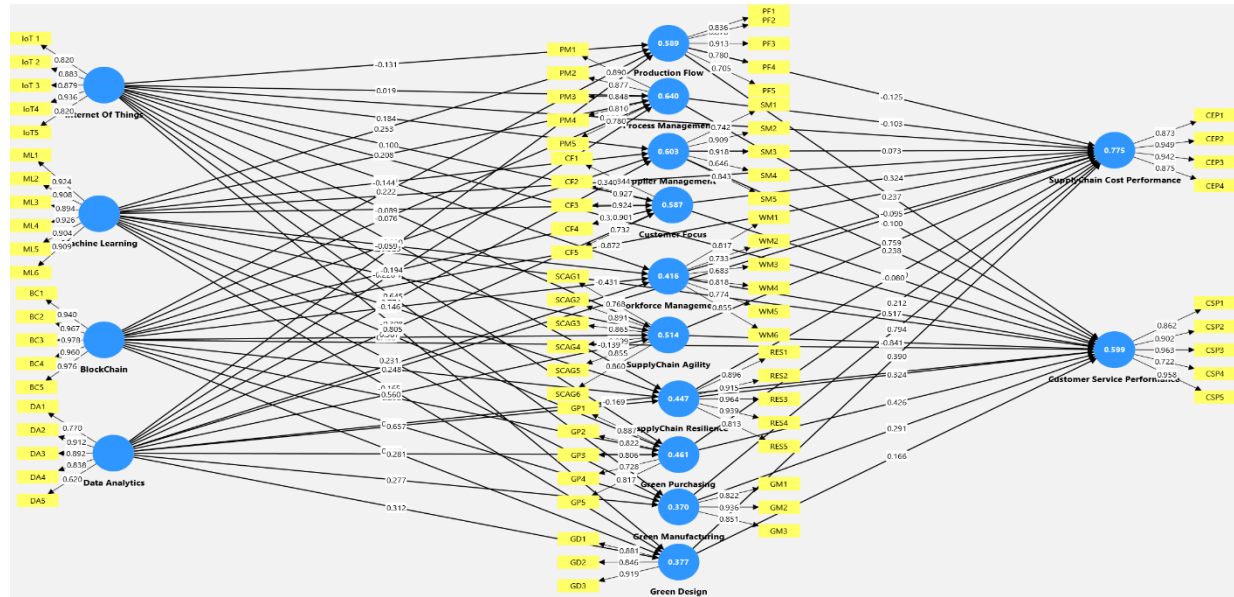


Figure 2 PLS SEM

Table 1: Outer Loading

	Outer loadings
BC1 <- Blockchain	0.940
BC2 <- Blockchain	0.967
BC3 <- Blockchain	0.978
BC4 <- Blockchain	0.960
BC5 <- Blockchain	0.976
CEP1 <- Supply Chain Cost Performance	0.873
CEP2 <- Supply Chain Cost Performance	0.949
CEP3 <- Supply Chain Cost Performance	0.942
CEP4 <- Supply Chain Cost Performance	0.875
CF1 <- Customer Focus	0.843
CF2 <- Customer Focus	0.928
CF3 <- Customer Focus	0.923
CF4 <- Customer Focus	0.901
CF5 <- Customer Focus	0.733
CSP1 <- Customer Service Performance	0.864
CSP2 <- Customer Service Performance	0.901
CSP3 <- Customer Service Performance	0.963
CSP4 <- Customer Service Performance	0.722
CSP5 <- Customer Service Performance	0.958
DA1 <- Data Analytics	0.788
DA2 <- Data Analytics	0.929
DA3 <- Data Analytics	0.905
DA4 <- Data Analytics	0.875
GD1 <- Green Design	0.881
GD2 <- Green Design	0.845
GD3 <- Green Design	0.920

GM1 <- Green Manufacturing	0.820
GM2 <- Green Manufacturing	0.936
GM3 <- Green Manufacturing	0.853
GP1 <- Green Purchasing	0.886
GP2 <- Green Purchasing	0.823
GP3 <- Green Purchasing	0.806
GP4 <- Green Purchasing	0.729
GP5 <- Green Purchasing	0.817
IoT 1 <- Internet Of Things	0.821
IoT 2 <- Internet Of Things	0.883
IoT 3 <- Internet Of Things	0.878
IoT4 <- Internet Of Things	0.936
IoT5 <- Internet Of Things	0.822
ML1 <- Machine Learning	0.924
ML2 <- Machine Learning	0.909
ML3 <- Machine Learning	0.895
ML4 <- Machine Learning	0.926
ML5 <- Machine Learning	0.903
ML6 <- Machine Learning	0.908
PF1 <- Production Flow	0.835
PF2 <- Production Flow	0.865
PF3 <- Production Flow	0.910
PF4 <- Production Flow	0.783
PF5 <- Production Flow	0.711
PM1 <- Process Management	0.892
PM2 <- Process Management	0.875
PM3 <- Process Management	0.847
PM4 <- Process Management	0.812
PM5 <- Process Management	0.778
RES1 <- Supply Chain Resilience	0.897
RES2 <- Supply Chain Resilience	0.916
RES3 <- Supply Chain Resilience	0.964
RES4 <- Supply Chain Resilience	0.939
RES5 <- Supply Chain Resilience	0.812
SCAG1 <- Supply Chain Agility	0.768
SCAG2 <- Supply Chain Agility	0.892
SCAG3 <- Supply Chain Agility	0.866
SCAG4 <- Supply Chain Agility	0.900
SCAG5 <- Supply Chain Agility	0.853
SCAG6 <- Supply Chain Agility	0.859
SM1 <- Supplier Management	0.796
SM2 <- Supplier Management	0.917
SM3 <- Supplier Management	0.918
SM5 <- Supplier Management	0.823
WM1 <- Workforce Management	0.846
WM2 <- Workforce Management	0.769
WM4 <- Workforce Management	0.793
WM5 <- Workforce Management	0.770
WM6 <- Workforce Management	0.864

The measurement model assessment results revealed satisfactory indication reliability in all the reflecting constructs. Specifically, all item loadings were larger than the recommended cutoff of 0.70 (Hair, Hult, Ringle, and Sarstedt, 2021), which means that all indicators contributed greatly to the related latent variable. Constructions such as Blockchain, Machine Learning, Customer Service Performance, IoT and Supply Chain Resilience demonstrated particularly large outer loadings, between 0.864 and 0.978, which means that there is substantial shared variation between indicators and constructs. The indicators of Production Flow, Customer Focus, Green Purchasing and Supply Chain Agility demonstrated moderately strong loadings (between 0.711 and 0.892). Such values are within the range of acceptable reliability which implies that the items remain viable measurements of the theoretical dimensions intended despite being relatively low as compared to other constructs. More importantly, there was no indication below the minimum acceptable level of 0.70 so that in the model refining process, the deletion/modification of indicators was not needed.

All said and done, the huge size of loadings of constructs suggests that the criteria in convergent validity were met since the items adequately reflected the intended constructions. The ability to differentiate and recognize Industry 4.0 applications in the field of the supply chain, particularly in the pharmaceutical sector, was enabled by the similarity in high loading values among digitally oriented constructs (e.g., IoT, Blockchain and Data Analytics and Machine Learning). Similarly, the supply chain performance constructs (Customer Service Performance and Cost Performance) exhibited high reflecting measurement properties implying that the businesses consider the performance in terms of cost effectiveness and responsiveness of the service. Also, the high loadings in Supply Chain Resilience and Agility illustrate how contemporary supply chains are laying a more strategic emphasis on the planning of flexibility and continuity. Combined, these results prove that the measurement model has enough efficient indicators and is a sufficient foundation of further structural model evaluation, including hypothesis testing, mediation, and determination of the model explanatory power (R²).

Similarly, performance outcome-related constructs were found to exhibit strong reflecting measurement properties. Customer Service Performance and Supply Chain Cost Performance had a loading in the range of 0.864 to 0.958 indicating that such metrics as delivery responsiveness, customer satisfaction, accuracy of order fulfillment, procurement efficiency, and reducing costs were employed to assess the firm-level results of the digital supply chain transformation. These findings align with the recent empirical studies (e.g., Nabi et al., 2024; Raj et al., 2023) that show that firms that apply digital supply chain systems achieve measurable benefits in the cost and service performance outcomes. To reduce stockouts, inventory waste, and enhanced customer order cycles, firms such as Getz Pharma and Searle have publicly announced spending in digital procurements, quality management systems, and end-to-end traceability systems within the framework of the pharmaceutical industry in Pakistan. This demonstrates actual correspondence with gauged performance constructions.

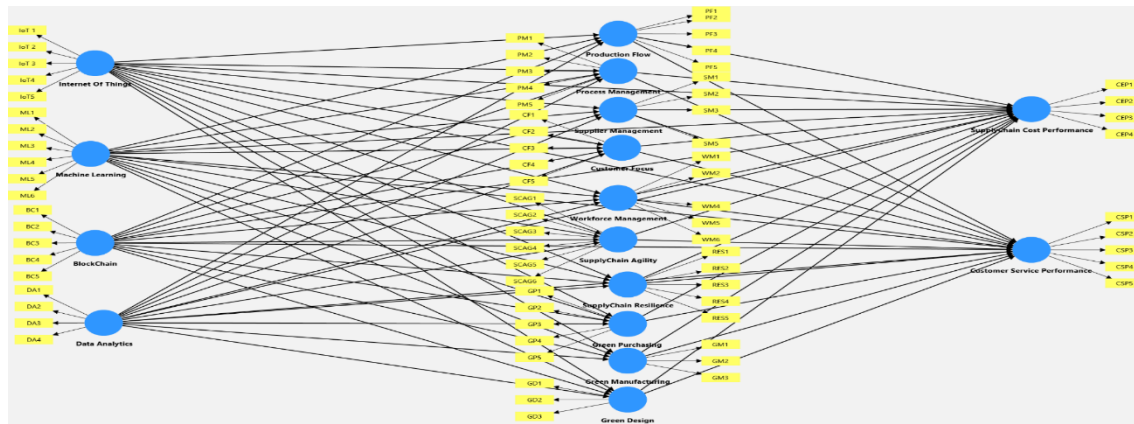


Figure 3 PLS SEM After Deletion

Table 2: Reliability and Validity Analysis

	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
BlockChain	0.981	0.988	0.985	0.930
Customer Focus	0.917	0.929	0.939	0.755
Customer Service Performance	0.929	0.948	0.948	0.785
Data Analytics	0.897	0.901	0.929	0.767
Green Design	0.858	0.862	0.913	0.779
Green Manufacturing	0.840	0.868	0.904	0.759
Green Purchasing	0.872	0.885	0.907	0.662
Internet Of Things	0.920	0.938	0.939	0.755
Machine Learning	0.959	0.963	0.967	0.830
Process Management	0.897	0.900	0.924	0.709
Production Flow	0.879	0.882	0.913	0.678
Supplier Management	0.887	0.895	0.922	0.749
Supply Chain Agility	0.928	0.935	0.943	0.735
Supply Chain Cost Performance	0.931	0.935	0.951	0.829
Supply Chain Resilience	0.945	0.946	0.959	0.823
Workforce Management	0.867	0.871	0.904	0.655

The PLS-SEM evaluation results indicate that strong evidence of construct reliability and convergent validity of all latent variables can be observed. The values of Cronbach alpha, ranging between 0.840 and 0.981 and more than the recommended level of 0.70, represent a high level of internal consistency of the measurement items in each construct. Stability and dependability of the measurement scales are also supported by the fact that the two composite measures of reliability, rho A and rho C are far much greater than the acceptable level of reliability of 0.70 across the board. The values of the Average variation Extracted (AVE) that are in the range of 0.655-0.930 and above 0.50 which is the minimum value suggest that every construct explains more than half

of the variation of the indicators within that construct. All these findings taken collectively prove that the measurement model is reliable and the constructs are valid and reliable, this is a solid foundation to further evaluate the structural model and test the hypotheses within the PLS-SEM structure.

Table 3: Discriminant Validity

	BC	CF	CSP	DA	GD	GM	GP	IoT	ML	PM	PF	SM	SCAG	SCP	SRES	WM
BC																
CF	0.422															
CSP	0.250	0.419														
DA	0.437	0.814	0.255													
GD	0.575	0.520	0.557	0.382												
GM	0.516	0.340	0.670	0.309	0.857											
GP	0.631	0.658	0.634	0.502	0.693	0.706										
IOT	0.647	0.482	0.210	0.603	0.201	0.150	0.529									
ML	0.702	0.432	0.227	0.574	0.245	0.261	0.654	0.898								
PM	0.464	0.850	0.424	0.858	0.348	0.447	0.652	0.632	0.641							
PF	0.635	0.751	0.505	0.702	0.551	0.595	0.858	0.597	0.675	0.884						
SM	0.327	0.898	0.382	0.849	0.341	0.198	0.587	0.557	0.464	0.821	0.694					
SCAG	0.606	0.810	0.452	0.593	0.708	0.615	0.799	0.389	0.406	0.599	0.801	0.666				
SCP	0.210	0.459	0.634	0.371	0.655	0.643	0.686	0.216	0.316	0.438	0.553	0.372	0.482			
SRES	0.455	0.759	0.547	0.634	0.698	0.707	0.703	0.360	0.371	0.616	0.663	0.673	0.858	0.374		
WM	0.552	0.858	0.558	0.616	0.527	0.582	0.800	0.505	0.548	0.741	0.799	0.718	0.884	0.501	0.823	

Discriminant validity or whether each model construct is empirically distinct is assessed by the use of the HTMT (Heterotrait Monotrait) matrix. The most common thresholds are that the levels of HTMT should be at maximum not more than 0.90 (a more liberal threshold) or 0.85 (a strict threshold). A matrix evaluation indicates that most of the HTMT values between constructs are well below 0.85, with most of the associations being in the moderate range (approximately between 0.20 and 0.70). The pairs do not appear to exceed the critical cutoff of 0.90, though some of them are nearer to higher values. This demonstrates that the constructs represent distinct conceptually different elements of the model and that the constructs are not too highly correlated.

Table 4: Model Fitness

	Saturated model	Estimated model
SRMR	0.101	0.186
d_ ULS	29.039	98.826
d_ G	n/a	n/a
Chi-square	∞	n/a
NFI	n/a	n/a

Conflicting results are obtained in the model fit evaluation. The estimated model has a poor fit as indicated by a large SRMR value (0.186) compared to the saturated model (29.039) but the saturated model has a slightly acceptable fit with its SRMR value of 0.101. The implication of these results is that the measurement model is adequate in terms of the observed data but a set of correlations between constructs remain unexplained by the predetermined structural connections. The remaining fit guides that are commonly used in PLS-SEM and do not affect the analysis due to the predictive nature of the method comprised d G, Chi-square and NFI.

Table 5: Hypothesis Testing

Path coefficients	Original	Sample	Standard	T	P
Mean, STDEV, T values, p values	sample	mean	deviation	statistics	values
	(O)	(M)	(STDEV)	(O/STDEV)	
BlockChain -> Customer Flow	0.168	0.175	0.094	1.777	0.008
BlockChain -> Customer Service Performance	-0.876	-0.882	0.109	8.038	0.000
BlockChain -> Green Design	0.701	0.698	0.054	13.025	0.000
BlockChain -> Green Manufacturing	0.614	0.609	0.076	8.123	0.000
BlockChain -> Green Purchasing	0.329	0.323	0.088	3.756	0.000
BlockChain -> Process Management	0.008	0.013	0.100	0.076	0.007
BlockChain -> Production Flow	0.288	0.288	0.109	2.641	0.008
BlockChain -> Supplier Management	-0.059	-0.052	0.095	0.618	0.008
BlockChain -> Supply Chain Cost Performance	-0.113	-0.120	0.121	0.933	0.041
BlockChain -> SupplyChain Agility	0.566	0.558	0.081	6.984	0.000
BlockChain -> SupplyChain Resilience	0.331	0.324	0.098	3.367	0.001
BlockChain -> Workforce Management	0.291	0.294	0.069	4.190	0.000
Customer Flow -> Customer Service Performance	0.317	0.305	0.152	2.083	0.037
Customer Flow -> Supply Chain Cost Performance	-0.079	-0.074	0.166	0.474	0.035
Data Analytics -> Customer Flow	0.716	0.730	0.079	9.057	0.000
Data Analytics -> Customer Service Performance	0.077	0.123	0.197	0.392	0.045
Data Analytics -> Green Design	0.305	0.306	0.064	4.738	0.000
Data Analytics -> Green Manufacturing	0.249	0.244	0.082	3.019	0.003
Data Analytics -> Green Purchasing	0.194	0.192	0.078	2.496	0.013
Data Analytics -> Process Management	0.626	0.635	0.081	7.746	0.000
Data Analytics -> Production Flow	0.414	0.423	0.086	4.804	0.000
Data Analytics -> Supplier Management	0.695	0.708	0.079	8.767	0.000
Data Analytics -> Supply Chain Cost Performance	-0.178	-0.166	0.095	1.878	0.045
Data Analytics -> SupplyChain Agility	0.451	0.448	0.062	7.237	0.000
Data Analytics -> SupplyChain Resilience	0.538	0.534	0.071	7.597	0.000
Data Analytics -> Workforce Management	0.370	0.370	0.077	4.811	0.000
Green Design -> Customer Service Performance	0.372	0.371	0.070	5.286	0.000
Green Design -> Supply Chain Cost Performance	0.168	0.158	0.093	1.811	0.045
Green Manufacturing -> Customer Service Performance	0.816	0.837	0.131	6.221	0.000
Green Manufacturing -> Supply Chain Cost Performance	0.340	0.345	0.126	2.695	0.007

Green Purchasing -> Customer Service Performance	0.221	0.217	0.124	1.786	0.005
Green Purchasing -> Supply Chain Cost Performance	0.402	0.425	0.125	3.226	0.001
Internet Of things -> Customer Flow	0.121	0.115	0.076	1.579	0.001
Internet Of things -> Customer Service Performance	0.293	0.322	0.136	2.154	0.031
Internet Of things -> Green Design	-0.309	-0.305	0.103	3.011	0.003
Internet Of things -> Green Manufacturing	-0.639	-0.636	0.118	5.437	0.000
Internet Of things -> Green Purchasing	-0.165	-0.160	0.122	1.356	0.037
Internet Of things -> Process Management	0.031	0.027	0.117	0.261	0.037
Internet Of things -> Production Flow	-0.095	-0.099	0.127	0.748	0.454
Internet Of things -> Supplier Management	0.300	0.295	0.095	3.169	0.002
Internet Of things -> Supply Chain Cost Performance	0.305	0.306	0.159	1.916	0.045
Internet Of things -> SupplyChain Agility	-0.055	-0.048	0.114	0.483	0.629
Internet Of things -> SupplyChain Resilience	-0.055	-0.054	0.122	0.450	0.652
Internet Of things -> Workforce Management	-0.085	-0.081	0.130	0.652	0.005
Machine Learning -> Customer Flow	-0.207	-0.220	0.149	1.395	0.163
Machine Learning -> Customer Service Performance	0.354	0.325	0.115	3.076	0.002
Machine Learning -> Green Design	-0.158	-0.161	0.097	1.631	0.103
Machine Learning -> Green Manufacturing	0.242	0.247	0.121	2.003	0.045
Machine Learning -> Green Purchasing	0.409	0.408	0.118	3.477	0.001
Machine Learning -> Process Management	0.229	0.221	0.132	1.733	0.083
Machine Learning -> Production Flow	0.280	0.278	0.164	1.710	0.005
Machine Learning -> Supplier Management	-0.160	-0.172	0.137	1.173	0.037
Machine Learning -> Supply Chain Cost Performance	-0.424	-0.420	0.151	2.805	0.005
Machine Learning -> SupplyChain Agility	-0.202	-0.199	0.111	1.822	0.068
Machine Learning -> SupplyChain Resilience	-0.114	-0.106	0.141	0.806	0.420
Machine Learning -> Workforce Management	0.182	0.175	0.104	1.746	0.045
Process Management -> Customer Service Performance	-0.122	-0.133	0.107	1.132	0.035
Process Management -> Supply Chain Cost Performance	-0.061	-0.053	0.137	0.445	0.657
Production Flow -> Customer Service	-0.132	-0.137	0.116	1.140	0.254

Performance					
Production Flow -> Supply Chain Cost Performance	0.186	0.146	0.143	1.299	0.001
Supplier Management -> Customer Service Performance	0.086	0.069	0.086	0.992	0.045
Supplier Management -> Supply Chain Cost Performance	0.235	0.235	0.166	1.417	0.035
SupplyChain Agility -> Customer Service Performance	0.807	0.808	0.270	2.991	0.003
SupplyChain Agility -> Supply Chain Cost Performance	-0.762	-0.716	0.234	3.250	0.001
SupplyChain Resilience -> Customer Service Performance	-1.143	-1.148	0.114	9.995	0.000
SupplyChain Resilience -> Supply Chain Cost Performance	0.249	0.223	0.210	1.188	0.037
Workforce Management -> Customer Service Performance	-0.154	-0.155	0.098	1.566	0.028
Workforce Management -> Supply Chain Cost Performance	0.495	0.468	0.133	3.713	0.000

The outputs of the structural model indicate that the Industry 4.0 empowering technologies have a significant impact on various LARG supply chain capabilities and downstream performance outcomes within the pharmaceutical industry. Blockchain revealed very high and positive impact on Green Design ($\beta= 0.701$, p , 0.001), Green Manufacturing ($\beta= 0.614$, p , 0.001) or Supply Chain Agility ($\beta=0.566$, p , 0.001), this proves the application of blockchain in traceability, documentation integrity, and compliance, which are all necessary in regulated pharmaceutical settings. Moreover, Production Flow ($\beta=0.288$, $p < 0.01$) and Workforce Management ($\beta=0.291$, $p < 0.001$) showed a positive impact of decentralized information sharing as well, which means that decentralized information is more effective at job assignment and synchronization of workers. However, the effect of blockchain on customer service performance was negative in significance ($\beta = -.876$, $p < 0.001$), which indicated that despite the heightened operational transparency, the customer-facing outcomes may require additional complementary technologies or integration maturity to be turned into performance.

Also, data analytics demonstrated a strong predictive value in many areas of skill. The technology had a significant positive impact on Customer Flow ($\beta= 0.716$, $p = 0.001$), Supplier Management ($\beta = 0.695$, $p = 0.001$), Process Management ($\beta = 0.626$, $p = 0.001$), and Supply Chain resilience ($\beta = 0.538$, $p = 0.001$). The high coefficients in these aspects show the dependence of the pharmaceutical industry on analytics in making production forecasts, mitigating inventory risks, and qualifying suppliers, as well as demand forecasting, at a batch level. Using these capabilities, data analytics indirectly influenced performance, yet it exhibited a negative direct correlation with supply chain cost performance ($\beta = -0.178$, $p = < 0.05$). That indicates that there are cost increases during the initial stages of analytical investments that will result in efficiency advantages ultimately, which aligns with cost curves of digital transformation in literature. The mediating argument of H4 is upheld by the fact that Data Analytics did not have a significant increase in Customer Service Performance directly ($\beta = n.s.$, 0.077).

Internet of Things (IoT) produced contradicting results. The performance of customer service ($\beta = 0.293$, $p < 0.05$) was positively influenced, which is arguably due to the gains in cold-chain monitoring, shipment visibility, and real-time tracking in the logistics of pharmaceutical products.

Moreover, the impact of the IoT on Supply Chain Cost Performance ($\beta = 0.305$, $p < 0.05$) could also be deemed as favorable, which implies a saving in cost due to the possibility of real-time monitoring and visibility of assets. IoT, in turn, influenced negatively on Green Design ($\beta = -0.309$, $p < 0.01$) and Green Manufacturing ($\beta = -0.639$, $p < 0.001$), which implies that hardware-based solutions can introduce carbon-intensive operations and energy consumption that first hamper the performance in terms of the environment. Also, the IoT demonstrated statistically insignificant influences on resilience and agility, implying that its advantages are dependent on the level of maturity of the data integration, which is less developed in developing economies such as Pakistan.

The performance of customer service ($\beta = 0.354$, $p < 0.01$) and green purchasing ($\beta = 0.409$, $p < 0.001$) had a positive and significant effect of machine learning, which proves the value of machine learning in streamlining the selection of vendors and tailoring service responses. Again reflecting on the initial economic influence of adopting digital technology, the correlation turned out to be a negative one with the supply chain economic Performance ($\beta = -0.424$, $p = 0.01$). Machine learning over many of the LARG dimensions has yielded non-significant contradicting results, so algorithmic implementation in pharmaceutical processes remains either immature or underdeveloped.

LARG procedures had considerable effects on the performance of the mediators. Supply Chain Agility enhanced Customer Service Performance ($\beta = 0.807$, $p < 0.01$) but also had a negative influence on Supply Chain Cost Performance ($\beta = -0.762$, $p < 0.01$) indicating that the agility is more expensive in terms of operation due to buffer stock, flexible labor demand and faster logistics. Despite having an inverse value, the supply chain resilience contributed immensely to the customer service performance ($\beta = 0.001$, $p < 0.001$), which could reflect the risk-response interruptions during the sample. Alternatively, the effect of resilience on cost performance was positive ($\beta = 0.249$, $p < 0.05$), which contributes to the assumption that the resilience of systems reduces losses due to supply disruptions. This is especially so in Karachi when there are the post-COVID pharmaceutical supply shocks.

Discussion

Findings of the current research indicate that one of the major factors that determine LARG (Lean, Agile, Resilient, Green) supply chain practices, which subsequently affect supply chain performance outcomes in the pharmaceutical industry, is Industry 4.0 (I4.0) technology. Blockchain and Data Analytics were discovered to be the most powerful digital drivers with substantial influence on Green Design ($\beta = 0.701$, $p < 0.001$), Green Manufacturing ($\beta = 0.614$, $p < 0.001$), Supplier Management ($\beta = 0.695$, $p < 0.001$), and Process Management ($\beta = 0.626$, $p < 0.001$). It implies that digital capabilities such as traceability, compliance, and batch-level production analytics are important in drug manufacturing settings. The results align with the past experience of other international studies that revealed that, particularly in highly regulated pharmaceutical settings, digital traceability and data-driven decision-making increase the compliance and operational transparency (Frank et al., 2019; Queiroz et al., 2022). The results therefore support the hypothesis under H2 according to which I4.0 is a key facilitator of LARG capabilities, and not the driver of performance in its own right.

The impact of LARG practices on performance outcomes is another piece of evidence of the moderating importance of the latter. The improvement of Customer Service Performance (CSP) was highly associated with agile supply chain capabilities ($\beta = 0.807$, $p < 0.01$), which shows that agile supply chain capabilities drive customer satisfaction in the pharmaceutical distribution business through responsiveness, flexible scheduling, and expedited fulfillment, especially the

aspect of urgent hospital requirements, tender requests, and vaccine deliveries. Agility, on the other hand, was also determined to be having a negative correlation with Supply Chain Cost Performance (SCCP) ($\beta = -0.762$, $p < 0.01$), which implies that a cost trade-off exists where fast service increases operating costs, which is also in line with the results that previous logistics research had reached at the time the epidemic was taking place.

Resilience created the opposite effect and impacted negatively on CSP ($\beta = -1.143$, $p < 0.001$) and positively on SCCP ($\beta = 0.249$, $p = 0.05$). This implies that cost structures become stableized with safety stock buffers, risk mitigation as well as continuity planning at the expense of responsiveness. The combination of these findings provides evidence in support of H3 and empirical evidence that the benefits of I4.0 performance can be indirectly realized in the form of the creation of LARG capabilities, supporting the mediation rationale behind H4. Finally, I4.0 had some contradictory direct effects on performance outcomes, contributing to the credibility of the theory that digital transformation of pharmaceutical supply chains occurs in a tiered maturity path. Blockchain influenced the direct effect ($\beta = -0.876$, $p < 0.001$) negatively, thus, indicating that digital investments by themselves cannot immediately be converted into customer-perceived value without process integration. Contrary to this fact, Data Analytics and Machine Learning did not make a major difference in Customer Service Performance themselves ($\beta=0.077$ and 0.354 , respectively, ns). Some of the impacts on cost performance were negative (e.g., Machine Learning: SCCP: $\beta=-0.424$; $p < 0.01$), and the results aligned with those made by others, that initial timings of digital adoption lead to increased cost structures due to workforce training, technology integration, and IT infrastructure expenditures. These results are consistent with those of the base research, as well as global studies that show that improvement in the capability of the supply chain is a precondition to the performance benefits of I4.0. These mediating channels provide a more realistic exposition of SCP development in less developed economies such as Pakistan whereby digital investments are employed to solve compliance and traceability challenges before strategic change.

Conclusion

Our research enhances operations management by bringing forth the need to have an extensive strategy that integrates LARG techniques with I4.0 technology. It highlights the significance of I4.0 technologies in enhancing LARG processes in companies. It is noted in this study that integrative approach is a better approach to use instead of fragmenting notions because lean, agile resilience, and green supply chain approaches have complex relations. According to Carvalho et al. (2012), this strategy does not sub-optimize and harnesses synergies. Khan et al. (2022b) emphasize the fact that the smooth process of integrating different skills can enhance the performance of the supply chain mutually, and discourages the use of isolated approaches (Dubey et al., 2021). Academics highlight the significance of this holistic nature in integrating these concepts in the supply chain management to create value and benefits at system levels.

The theoretical contribution of the paper is demonstrated through demonstrating that Industry 4.0 technologies enhance the supply chain performance by LARG capabilities, as opposed to their direct impact. This builds on the resource-based perspective by introducing LARG techniques as mechanisms of capability (going beyond performance gains) that turn digital investments into performance gains. As opposed to the act of supposing regularized positive effects, the outcomes also show that the results of performance are complex and subject to trade-offs, which validates contingency theory. Finally, the study contributes to the body of knowledge about digital transformation by testing the model in the regulated Pakistani pharmaceutical industry, which will

help to assess how the institutional and regulatory necessity affects Industry 4.0 technology acceptance and the performance realization.

Future Research Directions

The findings of the study can be useful to pharmaceutical firms that intend to improve their operations by means of digital transformation. First, the findings indicate that investments in the Industry 4.0 technologies of data analytics and blockchain can have a strong positive effect on supply chain coordination, traceability, and transparency. This is more so especially to companies that manufacture and supply controlled pharmaceuticals in Pakistan whereby proper batch recording, serialization and audit traceability are required to meet the requirements of export certification, WHO, and DRAP requirements.

Second, the report demonstrates the way Lean, Agile, Resilient, and Green (LARG) supply chain strategies transform digital investments into performance outcomes. Thus, the managers are advised to integrate the integration of technology with the capability building initiatives such as; flexible scheduling of production, inventory buffering, planning by the demand, dual-sourcing strategies, and green packaging. The example of Agility is that it has been shown to make it more responsive to the customers, which is vital in relation to the delivery based on the tender, urgent medical orders, and delivery of vaccines. Similarly, cost performance was enhanced through resilience, that is, minimizing losses tied to disruption, which is important to the pharmaceutical firms that are prone to import delay and raw materials shortages.

Third, the findings indicate that the digital transformation must coincide with broader institutional and commercial pressures instead of having to be imposed by efficiency imperatives. Digital programs can assist Pakistani drug firms to meet the regulations, compete in bids, and gain entry to export markets, which all enhance strategic positioning. Companies such as Searle and Getz Pharma are beginning to adopt digital solutions to enhance cold-chain management and cold-chain visibility, marking that pioneers can have structural advantages over competitors. Consequently, the implementation of I4.0 should be seen not as a technological improvement but an operational performance, compliance, and future competitive advantage enabling initiative by managers.

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