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Analytic Hierarchy Process based Prioritization of Organizational Practices and Drivers for Supply Chain Flexibility and Sustainability in Pharmaceutical Sector

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Abstract
Supply Chains (SC) are undergoing rapid transformation with the advent of Industry 4.0 (I4.0) technologies. In highly dynamic and volatile market conditions, Supply Chain Flexibility (SCF) that is the capability to adapt and respond to dynamic changes in the market environment and Supply Chain Sustainability (SCS) that is the ability of managing SCs to meet sustainability requirements and improve performance have become strategically critical. Despite growing interest, limited research has quantitatively examined which factors create the greatest synergy between SCF and SCS. This study addresses this gap by quantitatively prioritizing Organizational Practices (OP) and Underlying Drivers (UD) in the SC of pharmaceutical context using the Analytic Hierarchy Process (AHP). Findings reveal that OP such as 'Integration of sustainability principles into SCF' and 'Instrumental, interconnected and intelligent SC' holds the highest relative importance, demonstrating its dominant influence on the decision context and UD such as 'Transparency, Traceability and Visibility' holds the highest relative significance, exhibiting its dominant effect in the decision environment, followed by 'Technological changes/ adoption' and 'Resilience' have the highest impact on achieving simultaneous improvements in flexibility and sustainability. The results provide a structured decision hierarchy, highlighting actionable areas for managerial investment and resource allocation. By identifying and ranking these key enablers, the study demonstrates that SCF and SCS can co-evolve rather than compete, offering both practical guidance for pharmaceutical managers and a foundation for future research on optimizing SC performance in the digital era.

Keywords- Supply chain flexibility, Flexibility, Supply chain, Supply chain sustainability, Sustainability, Industry 4.0.

1. Introduction

Complexity, ambiguity, vulnerability, and uncertainty in the business environment have made it challenging for enterprises to manage their operations effectively. As a result, gaining a competitive edge requires aligning the entire value chain toward flexibility (Singh et al., 2023). Flexibility is essential for responding to variations in raw material supply and product demand. Pharmaceutical enterprises worldwide, including those in China and India, demonstrated flexibility during the COVID-19 pandemic by changing their production lines to meet the growing demand for medical supplies and vaccinations (Avinash and Joseph, 2025). The pharmaceutical sector contributes significantly to global health by developing, manufacturing, and distributing drugs that improve quality of life and extend life expectancy. The industry has major environmental implications throughout the product life cycle, including raw material sourcing, production, distribution, use, and disposal. In recent years, there has been increased focus on understanding and improving pharmaceutical company's environmental sustainability performance, particularly in light of growing regulatory pressure, consumer awareness, and the global commitment to Sustainable Development Goals (SDGs) under the United Nations Agenda 2030 (Eshun and Odamtten, 2025). Sustainability is the primary focus in pharmaceutical manufacturing due to regulatory requirements, company Environmental, Social, and Governance (ESG) goals, and global climate measures (Ali et al., 2025). The post-pandemic business environment is complex and uncertain, driving firms to examine and adjust their operational strategies. SCF is crucial for managing uncertainty and adapting strategies. In the post-epidemic period, firms across industries must integrate sustainability measures to address environmental issues. As organizations try to balance economic, environmental, and social responsibilities, SC management plays a crucial role in ensuring overall sustainability performance. SCF enables organizations to adjust quickly and effectively to changing market conditions, disturbances, and stakeholder expectations (Wang et al., 2024). Globalization, increased SC complexity, growing customer demands, shorter product and technology life cycles and an unstable climate provide significant uncertainties and dangers to the pharmaceutical SC. Uncertainty and risk have become an issue in SCs and managing that has become a top priority for pharmaceutical firms in both private and public sectors because of its significant impact on on-time delivery, efficiency, cost-effectiveness and customer satisfaction. Flexible SCs enable the entire ecosystem to adjust to a dynamic environment. It can improve efficiency, responsiveness of supplier networks, and promote globalization, innovation, and customer-centricity among enterprises (Singh et al., 2023).

Furthermore, the flexibility can be used to mitigate SC uncertainty and unprecedented risks (Wang and Jie, 2020). In order to create sustainable revenue streams from the development of specialized products and technologies, the pharmaceutical industry must transform into a lean, focused organization with extensive research and innovation operations in the current competitive market (Debnath et al., 2023). Concerns about hazardous waste that could endanger human health and the environment, the necessity of cost-effective SC methods, and the increasing demand for accountability and transparency in the production and distribution of pharmaceuticals are all expected to be addressed by the pharmaceutical industry. It is continually gaining attention in sustainability since it contributes to long-term economic, environmental, and social growth (Tetteh et al., 2024).

AHP allows management to describe decisions problem and then organize it into a multi-level hierarchy of decision aspects. The decision factors are then evaluated and weighted to determine which are the priority in the decision process. The AHP technique can help managers make a wide range of complicated decisions. Problems may include supplier selection, facility location decisions, forecasting, risk and opportunity modeling, technology selection, plan and product design, and so on (Gaudenzi and Borghesi, 2006).

It has been observed that prior studies examined SCF, SCS, and I4.0 individually or with other variables. But there remains a gap on understanding on which factors contribute to the synergy between SCF and SCS. In our study we take OP and UD to analyze the synergistic effect between SCF and SCS. Existing literature has not adequately prioritized these factors to determine their relative significance in fostering a balanced, flexible, and sustainable SC. Our study identifies OP and UD that creates synergy between SCF and SCS through literature and further we aim to prioritize those factors to ascertain which practices and drivers creates the most synergy between the two. Hence, there is a need for AHP-based prioritization. Our study addresses this gap by AHP-based prioritization of the OP and UD to ascertain which factors creates the most synergy between SCF and SCS. Following are the research objectives:

(i) To identify OP and UD that create synergy between SCF and SCS.
(ii) To prioritize the identified practices and drivers to determine which factors have the greatest impact on the synergy.

This study offers both theoretical and methodological contributions. Theoretically, it addresses the fragmented nature of existing literature by integrating SCF, SCS, and I4.0 within a single framework. Using the Context-Intervention-Mechanism-Outcome (CIMO) approach, the study systematically links the context of digitally evolving SC with relevant OP and UD. It explains how these contribute to improved flexibility and sustainability outcomes. Methodologically, the study goes beyond traditional empirical approaches by applying AHP to prioritize key OP and their UD. This structured approach provides deeper insights into the relative importance of factors influencing the synergy between SCF and SCS in the pharmaceutical SC.

In view of this, our research reveals several key findings. The key OP and UD were derived from the CIMO Table (for details see Section 2.5) and explained in the subsequent section. The finalized OP and UD were assessed to determine their relative importance using AHP through expert judgement (as explained in Section 4). The implications of the research are provided to ascertain and manage which factors create the most synergy between SCF and SCS (for details see Section 5 and 6). Following the introduction, Section 2 presents the literature review, Section 3 presents the Research Design Methodology, Section 4 presents the results and analysis, Section 5 presents the discussion and lastly Section 6 presents the conclusion.

2. Literature Review

This study searched the major databases, including Scopus and Google Scholar. The keyword selection is based on the concepts of sustainability, technology, and SCF. The general search string that was used for the database search was as follows:

"Title" OR "Abstract" OR "Keyword",
String 1: ("Supply Chain Flexibility" OR "Flexibility") AND ("Supply Chain").
String 2: ("Supply Chain Sustainability" OR "Sustainability") AND ("Supply Chain").
String 3: ("Industry 4.0").

The dates of publication were not constrained. After applying relevant filters, the approach identified 50 papers, which included articles, book chapters, conference papers, and reviews. From among these papers, 24 were accessible, with a few papers added later. Papers that were inaccessible or lacked sufficient relevance and methodological detail were excluded to maintain the reliability and consistency of the review.

2.1 Supply Chain Flexibility

According to Kumar et al. (2006) "SCF is the ability of SC partners to restructure their operations, align their strategies, and share the responsibility to respond rapidly to customers' demand at each link of the chain, to produce a variety of products in the quantities, costs, and quality that customers expect, while still maintaining high performance." Based on Winkler's (2009) definition, "SCF can be seen as an ability of a SC that helps to gain competitive advantage and improve success." It is a company's ability to absorb and reapply changes in the market environment (Singh et al., 2024). A flexible SC can help organizations respond quickly to unexpected environments, making it a strategic tool. It necessitates a high level of commitment and resource availability. Firms should create and align SCFs to address business uncertainty (Singh et al., 2023). Pharmaceutical companies should prioritize strategic flexibility to improve performance in an uncertain and unpredictable business environment (Ajike et al., 2024). Pharmaceutical enterprises may confront long-term challenges and risks related to economics, politics, operations, culture, environment and ethnicity. In the pharmaceutical sector, a flexible SC is crucial for effective interaction and resilience. It is crucial for delivering value to customers. Flexibility allows firms to efficiently adapt to changing market conditions. Furthermore, the flexibility can be used to mitigate SC uncertainty and hazards (Wang and Jie, 2020).

2.2 Supply Chain Sustainability

SCS is defined as "managing the SC functions aligned with the social, environmental, and economic sustainability requirements of the stakeholders to reduce sustainability risks in SC and improve market performance" (Chowdhury and Quaddus, 2021). "It implies the creation of coordinated SCs through the voluntary integration of economic, environmental, and social considerations with key inter-organizational business systems designed to efficiently and effectively manage the material, information, and capital flows associated with the procurement, production, and distribution of products or services in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short and long-term" (Sánchez-Flores et al., 2020). According to the triple bottom-line sustainability theory, SC managers must consider 'social, economic and environmental' objectives while selecting how to make their organization viable (Shashi, 2023). Sustainability in the pharmaceutical SC ecosystem involves balancing 'environmental, social, and economic' pillars. Indicators for sustainability development in pharmaceutical businesses should address all three areas of sustainability (Shashi, 2022). Sustainability is enhanced by flexibility and adaptability, particularly in unpredictable environments. Firm's social and environmental sustainability is greatly enhanced by SCF (Matarneh et al., 2024).

2.3 Industry 4.0 Intervention

Flexible SCs promote sustainable practices like 'green sourcing, carbon footprint reduction and responsible packaging'. This aligns with Corporate Social Responsibility (CSR) aims and improves brand reputation among environmentally sensitive customers. Technological improvements improve SCF and allow for adaptive marketing strategies. In addition to improving SC visibility, transparency, and decision-making, technologies like 'Artificial Intelligence (AI), Internet of Things (IoT), Blockchain Technology (BCT), and Cloud Computing (CC)' also help businesses boost operational efficiencies, SC resilience, and offer individualized customer experiences, giving them a competitive edge and long-term growth (Holloway, 2024).

New technologies have rapidly evolved in various industries, including pharmaceuticals. The pharmaceutical sector has recently seen the introduction of new technologies such as AI, BCT and telemedicine, among others, which are projected to further improve the industry. AI-based services have enormous potential for improving the process of customized medicine because the AI engine can recognize specific patient profiles and prescribe a course of therapy. BCT is considered as a technique of protecting SCs, preventing counterfeit drugs, and making pharmaceutical transactions transparent (Ahalawat et al., 2025). As Sayal et al. (2023) states one potential application of BCT is the verification of sustainability claims. Technologies such as Big Data Analytics (BDA), CC, BCT and IoT could provide effective resource management and flexible manufacturing, which would improve overall SCS and a company's ability to respond proactively to sustainability concerns (Matarneh et al., 2024). Using Pharma I4.0 technology creates sustainable value, leads to a more flexible, smart and personalized pharma industry and provides enterprises with long-term competitive advantages. 3D printing enhances manufacturing productivity and flexibility, enables personalized medication, reduces material waste throughout the product life cycle, and promotes environmentally sustainable and energy-efficient manufacturing. Transparent and real-time information systems promote successful collaboration and communication among suppliers, manufacturers, distributors, hospitals, and end users. BDA can improve SCF and SCS by reducing human participation in decision-making, identifying possible risks, and implementing suitable policies to prevent disruptions (Ding, 2018). IoT improves visibility and visibility improves flexibility along with that, the same visibility reduces waste and emissions, supporting environmental sustainability. IoT deployment also affects their economic outcomes positively (Vass et al., 2021). Singh (2024) states that combining flexible SC methods with I4.0 technologies improves responsiveness and shorten lead times. In the context of sustainable SC performance, SCF will accelerate organizational capabilities to realign its operating practices towards sustainability targets, such as 'carbon reductions, resource efficiency, or response compliance', thereby contributing at a higher maturity level to sustainable and resilient SC. These technological advances are transforming the pharmaceutical business into digital, technology-dependent manufacturing systems. This transformation helps organizations use technology to operate efficiently, cost-effectively, and competitively. Although I4.0 began in manufacturing, it has greatly impacted strategic SC operations (Debnath et al., 2023). Holloway (2024) in the study discusses the integration of sustainability principles into SCF. Environmentally sustainable methods including 'green sourcing, eco-friendly packaging, and carbon footprint reduction' are impacting consumer purchasing decisions and market preferences. Flexible SCs help organizations meet consumer demand for sustainable products and practices, improve their CSR profiles and comply with regulatory constraints. Flexibility and sustainability work together by helping SCs adapt responsibly, and technology makes this possible through real-time data, transparency and smarter decisions.

2.4 The Dynamic Capabilities View

Dynamic Capability is "the ability to integrate, build, and reconfigure internal and external competencies to adjust in accordance with the rapidly changing environments" (Teece et al., 1997). The strategic ability of businesses, institutions, and organizations to innovate and adapt beyond the standard is known as dynamic capabilities (Kazancoglu et al., 2022). The existing literature puts forward various conceptualizations for the DCV (Dynamic Capabilities View). The most prevalent is that introduced by Teece with three principal aspects, i.e. 'sensing,' 'seizing,' and 'transforming' (Cheng et al., 2022). This description is consistent with the explanation of SCF. "Flexibility has been defined as the organization's ability to meet an increasing variety of customer needs without excessive costs, time, or performance losses" (Suh and Lee, 2018). SCF is considered as a capability in literature (Ramon-Jeronimo et al., 2017; Um et al., 2017). It is an organization's ability to provide a specialized and distinctive customer experience by providing a variety of services. Unpredictable circumstances, such as demand-supply gaps, shorter product life cycles, inventory management, fill rate, and technological improvements, drive academics to research novel resource-optimization solutions (Khanuja and Jain, 2022). SCF enables speedy and efficient responses to unanticipated market changes for both internal and external stakeholders (Shahadat et al., 2023). According to Teece (2007), businesses must prioritize the development of new processes, products, and business models in order to achieve exceptional performance. To develop dynamic capabilities, businesses should incorporate flexibility into their SC procedures, expanding on earlier reasoning. Organizations must combine internal and external resources, use technology, and meet market expectations (Khanuja and Jain, 2023). SCS is considered as a capability through the lens of DCV since it allows businesses to adapt, integrate, and restructure resources in response to environmental and societal concerns (Beske, 2012; Chowdhury et al., 2019). The DCV focuses on how organizations respond to changing environments by leveraging internal SCF capabilities and external SC agility. In a dynamic environment, particularly one with a high degree of customization, providing dynamic capacity, such as quick response in a SC, has a lot of potential (Um et al., 2017). Chowdhury and Quaddus (2021) empirically presents that SCS practices and governance mechanisms themselves act as dynamic capabilities, meeting Teece's "technical" and "evolutionary" fitness criteria, and enabling firms to mitigate sustainability risks and improve market performance.

2.5 Context-Intervention-Mechanism-Outcome (CIMO) Based Identification of Factors

The OP and UD considered in this study were identified through a comprehensive review of literature on I4.0, SCF, and SCS. The studies were analyzed using the CIMO logic to systematically extract relevant practices and drivers that contribute to the synergy between flexibility and sustainability. Based on this analysis, the identified factors were consolidated and refined to develop the final set used for prioritization. CIMO logic describes "what to do (Intervention), in which situations (Context), to produce what effect (Outcome) and provides an understanding of how the intervention generates the outcomes (Mechanisms)" (Denyer et al., 2008). It offers a structured strategy to synthesis research findings and enhances their practical utility. It also enables the generation of practical knowledge that can be used in numerous organizational situations (Pervez et al., 2025). **Table 1** presents the identification of factors using CIMO logic. The literature on I4.0, SCF, and SCS is fragmented, with studies examining these areas separately. In this context it is necessary to study the involvement of I4.0 technologies in SCF and SCS context as it acts as an enabler to create synergy between the two. To address this, the study uses the CIMO framework to organize and connect these concepts. Interventions include I4.0 technologies and OP adopted by firms.

These work through key mechanisms such as visibility, traceability, and collaboration. The outcomes are reflected in improved flexibility and sustainability performance. In this way, CIMO provides a clear structure to integrate existing research and explain how these elements are linked.

Table 1. Identification of factors using CIMO Logic.

S. No.	Reference	Context	Intervention		Mechanism	Outcome
		Purpose	**Technology used**	**Organizational practices**	**Underlying drivers**	**Synergy**
1.	Shukla et al. (2010)	The purpose is to compare sustainability and flexibility and to know whether incorporating flexibility has a negative impact or it enhances sustainability.	NA	Just-in-time, Collaborative planning, forecasting and replenishment (CPFR), Vendor managed inventory (VMI).	High service levels Responsiveness	Synergy
2.	Ding (2018)	The goal is to identify sustainability challenges in Pharmaceutical SC and explore how I4.0 may support sustainable Pharmaceutical SC paradigms.	3D printing Cyber-physical Systems	Green purchasing strategies, Conventional quality control strategy.	Responsiveness Transparency Traceability	Synergy
3.	Bag et al. (2018)	The study examines how flexibility affects sustainability in supply networks, taking into account institutional pressures and resource availability in steel and engineering sector.	NA	Purchasing strategy, Investment for changes in the existing production layout, Production process and material handling system to match with customer requirements.	Adaptability Resilience Risk management Innovativeness Technological changes	Synergy
4.	Liu et al. (2019)	Recognize the precise role SCF may play in implementing green operations efforts successfully in the automotive business.	NA	Environmental audit of suppliers, Supplier environmental certification, JIT, lean operation.	Degree of innovativeness in different green design initiatives	Synergy
5.	Gupta et al. (2019)	To analyzes the link and relevance of information system agility and smart SC features from the angle of organizational information processing theory in order to achieve SCF and sustainable SC in South Africa's manufacturing sector.	Technology in terms of digital infrastructure and smart SC	Incentive mechanism, Strengthening the supplier relationship, support more operations related to flexible information systems.	Information system agility	Synergy/ Integration

Table 1 continued…

6.	Thaiprayoon et al. (2019)	To understand the mediating effect of SCF between the various characteristics of smart city SC and the sustainability performance of Thailand's manufacturing industry.	NA	Instrumental, interconnected and intelligent SC.	Agile Adaptability	Synergy
7.	Vass et al. (2021)	Investigating the precise impact of IoT on sustainability and performance in Australian retail SC.	IoT	NA	Visibility Auto-capture Intelligence Information sharing	Synergy
8.	Zhou and Wang (2021)	construction, manufacturing, IT, logistics, retail industry, purchasing, logistics and manufacturing departments.	Digitization	Lean and elastic practices.	Collaborative knowledge creation	Synergy
9.	Matarneh et al. (2024)	Investigates the influence of I4.0 technologies and dynamic capabilities such as Sustainable SCF, on the sustainability of manufacturing firms in Pakistan.	IoT, sensors BDA BCT	Green SC through reverse logistics flexibility.	Real-time data utilization	Synergy/ Integration
10.	Singh (2024)	The objective is to facilitate the firm's sustainable growth while safeguarding future generation's capacity to meet their requirements in the tire business.	Real-time data analytics and IoT	Flexible SC strategies.	Responsiveness Reduce lead times	Synergy
11.	Holloway (2024)	Learn how organizations in various industries use SC flexibility to modify marketing campaigns to shifting consumer demands.	AI IOT BCT CC	Green sourcing, Eco-friendly packaging, Carbon footprint reduction initiatives.	Demand forecasting and decision-making processes Real-time data Visibility Transparency Traceability Scalable and collaborative SC operations Responsiveness Agility Resilience	Synergy

The synergy discussed here describes the mutually reinforcing relationship between SCF and SCS, where improvements in one capability enhance and support the performance of the other. For example, personalized medication is made possible by 3D printing, which also increases manufacturing productivity and flexibility, minimizes material waste throughout the product life cycle, and encourages energy-efficient and environmentally sustainable manufacturing (Ding, 2018). New product flexibility can assist firms in quickly adapting their innovative product offerings to altering consumer expectations for sustainability. A strong mix flexibility may also be required to incorporate new greener products into existing product portfolios, since it allows enterprises to efficiently and inexpensively generate multiple product combinations given a specific capacity. Strong modification flexibility enables organizations to implement product changes quickly and effectively, which is another prerequisite of green strategies, the use of sustainable resources in production (Liu et al., 2019). SCF enhances social and environmental sustainability by enabling firms to respond effectively to market uncertainty, disruptions, and evolving sustainability requirements. In dynamic environments, flexible SCs supported by technologies such as IoT, BCT, BDA, and CC improve resilience, resource efficiency, and overall sustainability performance (Matarneh et al., 2024; Zhou and Wang 2021).

2.6 Organizational Practices and Underlying Drivers

The identified OPs are shown in **Table 2**, whereas the UDs are listed in **Table 3**. These factors, collectively, help create synergy between SCF and SCS. This indicates the important aspects and enablers that help in effectively integrating flexibility and sustainability within the SC.

Table 2. Organizational practices.

OP	**Organizational Practices**	**Description/ Context**	**References**
OP 1	Lean Just-in-time (JIT) practices	It is a management philosophy focused on delivering value to customers by eliminating waste and optimizing processes. It encompasses several core principles, including value identification, value stream mapping, flow creation, pull-based production, and the pursuit of perfection. Suppliers are located nearby, which enables fast responses and just-in-time supply leading to flexibility in operations. Support of flexible suppliers is important for JIT and lean practices. JIT is tied to process improvement and lean paradigms, ensuring efficiency while reducing waste.	Liu et al. (2019), Shukla et al. (2010)
OP 2	CPFR, VMI	According to Panahifar et al. (2015) CPFR is defined as "Collaboration where two or more parties in the SC jointly plan a number of promotional activities and work out synchronized forecasts, on the basis of which the production and replenishment processes are determined". As per Guimarães et al. (2013) VMI is defined as "The practice of retailers making suppliers responsible for determining order size and timing, usually based on receipt of retail point of sale inventory data. Its goal is to increase retail inventory turns and reduce stock outs. It may or may not involve consignment of inventory (supplier ownership of the inventory located at the customer)".	Guimarães et al. (2013), Panahifar et al. (2015), Shukla et al. (2010)
OP 3	Green purchasing strategies	Green purchasing prioritizes using durable, recyclable and reusable materials to reduce environmental impact during manufacturing and shipping. The international green purchasing network defines green purchasing as acquiring products and services with minimal environmental impact and at comparable prices to demonstrate social responsibility and ethics.	Chin et al. (2020), Ding (2018)
OP 4	Purchasing strategy/ practices	It includes cost reduction, value analysis, improving delivery and increasing flexibility. It also consists of multiple sourcing, long-term relationships and inventory buffers across supply network.	Bag et al. (2018), Pérez-Pérez et al. (2019)
OP 5	Environmental audit of suppliers	In order to analyze the supplier's sustainability practices and compliance with sustainability requirements, including an evaluation of the social and environmental aspects of sustainability, it includes audits of the supplier's activities (headquarters and/or production sites).	Fraser et al. (2020) Liu et al. (2019)
OP 6	Strengthening the supplier relationship	It includes communication with suppliers, use of framework agreements, and performance monitoring systems. Effective supplier relationship management promotes flexibility, adaptation, resilience, and risk management.	Bag et al. (2018), Gupta et al. (2019), Kirema et al. (2025)
OP 7	Instrumental, interconnected and intelligent SC	An instrumented SC uses sensors, data networks, and digital tools to enable real-time visibility, efficiency and decision-making. It enhances sustainability and competitiveness through improved operations, asset management, and logistics integration. An interconnected SC enables seamless system-to-system integration across the supply network, enhancing collaboration, asset management, and inventory sustainability. It improves sustainability performance cost-effectively by supporting service-oriented architectures and aligning business planning, operations, and logistics capabilities. An intelligent SC leverages advanced analytics and next-generation optimization tools to enhance decision-making, efficiency, and sustainability performance. It integrates data-driven intelligence to manage complexity, promote environmental and social responsibility, and strengthen competitive and sustainability advantages.	Gupta et al. (2019), Martínez et al. (2016), Thaiprayoon et al. (2019), Zhang et al. (2017)
OP 8	Flexible SC strategies	It includes lead time flexibility to handle demand fluctuations, capacity for customization to meet diverse customer needs, cost efficiency under change to maintain competitiveness while adapting along with integration with IoT and real-time analytics to reduce lead times and improve responsiveness.	Singh (2024)
OP 9	Integration of sustainability principles into SCF	Environmentally sustainable methods, including 'green sourcing, eco-friendly packaging, and carbon footprint reduction' are impacting consumer purchasing decisions and market preferences. Flexible SCs enable companies to meet legal standards, enhance their CSR profiles, and react to growing customer demand for sustainable activities and goods.	Holloway (2024)

Table 3. Underlying drivers.

UD	Underlying drivers	Description/ Context	References
UD 1	Agility and Responsiveness	Capability to swiftly reconfigure processes and resources to accommodate changing market demands. Flexibility is a valuable skill that enhances sustainability and agility. Responsiveness is the capability of firm's SC to quickly respond to short-term and temporary changes. Understanding and adhering to the buyer's system is crucial for key suppliers to ensure sustainability. Furthermore, their openness to accept volume and variety adjustments contributes to meeting dynamic consumer requirements thereby improving SC responsiveness.	Bag et al. (2018), Ding (2018), Holloway (2024), Pérez-Pérez et al. (2019), Zhou and Wang (2021)
UD 2	Transparency, Traceability and Visibility	The CPS system increases the transparency and traceability of the distribution process. The transparent and real-time information systems motivate more effective collaboration and communication among various stakeholders, thereby mitigating any disruption, implementing appropriate strategies, leading to more flexible and sustainable SCs. Technology adoption supports traceability, leading to more sustainable and responsive SC. The instrumented SC is a crucial component of Smart Cities. It relies on pervasive data-collecting networks for real-time visibility. The sustainability performance model demonstrates how a well-instrumented SC can positively benefit corporate development. Technological advancements were cited as important drivers of SCF. These technologies improve SC operations, transparency and data-driven decision-making, enabling firms to be more agile and responsive in their SC and marketing strategies.	Ding (2018), Holloway (2024), Matarneh et al. (2024), Thaiprayoon et al. (2019), Vass et al. (2021)
UD 3	Resilience	Refers to the capability to recover swiftly from disruptions while maintaining continuity in SC operations. Building resilience in supply networks allows organizations to anticipate and adapt to market demands. Integrating sustainability and effective supplier relationship management improves SC adaptability, positioning organizations for long-term growth and competitiveness in global marketplaces.	Holloway (2024), Negri et al. (2021)
UD 4	Innovativeness	In order to increase flexibility, which will ultimately lead to increased innovation and sustainability in supplier networks, businesses should concentrate on green supplier development and create strong relationships with important suppliers. It is critical to develop a long-term procurement policy that is updated as the company's mission and vision evolve. Managers have a crucial role in driving cultural and technological changes that promote flexibility and innovation.	Bag et al. (2018)
UD 5	Technological changes/ adoption	Technology adoption is one of those instances where flexibility may be achieved in a sustainable manner. Technological innovation can enhance SCF by improving management efficiency. It also promotes enterprise change and renewal, positively impacting SCF.	Shukla et al. (2010), Zhou and Wang (2021)
UD 6	Adaptability	Sustainability is enhanced by flexibility and adaptability, particularly in unexpected environments. Improving SC adaptability is advantageous for SC management because it strengthens the chain's resistance to vulnerabilities and promotes its sustained operation.	Matarneh et al. (2024)
UD 7	Collaborative knowledge creation	Collaborative SC management involves upstream and downstream enterprises working together to achieve better economic, environmental, and social performance. Collaborative knowledge development initiatives may improve SC sustainability.	Zhou and Wang (2021)
UD 8	Demand forecasting	Real-time analytics data and flexible information systems enable demand forecasting and supplier collaboration, ensuring SC sustainability.	Singh (2024)

Previous studies have examined the relationships between I4.0, SCF and SCS. However, limited attention has been given to prioritizing the UD and OP that create synergy between these capabilities. In particular, the use of the AHP to systematically rank these factors remains underexplored. Therefore, this study aims to identify and prioritize the key factors that enable the synergy between SCF and SCS in the pharmaceutical SC.

3. Research Design Methodology: Analytical Hierarchy Process

AHP was invented by Saaty in the 1970s and has since been extensively explored. It is now utilized in decision-making for complicated scenarios, where individuals collaborate to make decisions where human perceptions, judgments and consequences have long-term repercussions. AHP converts comparisons into numerical numbers, which are subsequently analyzed and compared. The weight of each factor enables the evaluation of each element within the given hierarchy. When compared to other comparison techniques, the AHP technique's primary distinguishing feature is its capacity to translate empirical data into mathematical models. The comparison of two items using AHP can be done in multiple ways. Saaty's proposed importance scale for comparing two alternatives is frequently used. The scale evaluates the relative importance of one possibility in comparison to another by assigning values ranging from 1 to 9 as presented in **Table 4** (Badea et al., 2014; Saaty, 2008). The steps involved in AHP include:

(1) Identifying OP and UD from the CIMO analysis.
(2) Formation of pairwise comparison matrix through data collection by experts based on a nine-point Saaty's scale.
(3) Computation of the Eigen values, Eigen vectors and relative importance weights.
(4) The Consistency Ratio (CR) will be evaluated.

The CR measures the consistency of pairwise comparisons. The mathematical expression for determining the CR is:

$$CR = \frac{CI}{RI},$$

where, the Consistency Index is denoted by $(CI) = \frac{\lambda_{max} - n}{n-1}$ (λ_{max} is the maximum average value) and the value of the Random Consistency Index (*RI*) is dependent on the value of (*n*). For optimal consistency, the *CR* value should be less than 0.10 (Luthra et al., 2016).

AHP is employed as a solution methodology in this study. AHP simplifies, organizes, and analyzes difficult problems. The process creates a hierarchical structure for the problem, including goals, criteria, and sub-criteria. Several approaches, including ELECTRE and TOPSIS, have been proposed to address the multi-criterion decision-making problem. AHP is preferred above other tools for its versatility and ease of use (Luthra et al., 2016). Most studies examining I4.0, SCF and sustainability uses empirical approach such as SEM to examine relationship between constructs. While this approach provides valuable insights, it does not enable the systematic prioritization of the UD and OP influencing these capabilities. AHP offers a structured framework that allows identified factors to be evaluated through pairwise comparison and ranked according to their relative importance. The aim of this paper is to prioritize the OP and UD that contributes in enhancing synergy between SCF and SCS in I4.0-enabled pharmaceutical SCs. For that purpose, we have employed AHP to prioritize the factors. The criteria for the goal is 'synergy' among SCF and SCS through OP and UD. The alternatives for both are discussed in section 2.6. i.e. 9 alternatives for OP and eight alternatives for UD. The steps involved in adopted methodology is presented in **Figure 1**. The data for the present study has been collected from industry and academic experts (see **Table 5**). The use of three experts is consistent with prior AHP-based SC study where evaluations were conducted using small panels of highly specialized experts. A study by Aydin and Kahraman (2010), three experts evaluated suppliers using the proposed model and selected the most suitable supplier. Data was acquired by interviewing experts using a questionnaire based on Saaty's '1-9 scale'. In a study by Aydın and Kahraman (2019), three experts evaluate firms based on their background, experiences, and knowledge. While the study used a limited number of experts, the responses demonstrated acceptable CR as explained in results section ahead and provided meaningful insights for the analysis. For analysis we used template provided by Goepel (2018). Existing AHP-based studies have examined factors related to sustainability, flexibility, or technology adoption in SCs. However, limited attention has been given to integrating these dimensions within a single framework. This study addresses this gap by jointly examining SCF, SCS, and I4.0. It further focuses on how OPs and UDs support both flexibility and sustainability. In addition, the use of the CIMO framework enables a structured identification and organization of these factors prior to prioritization.

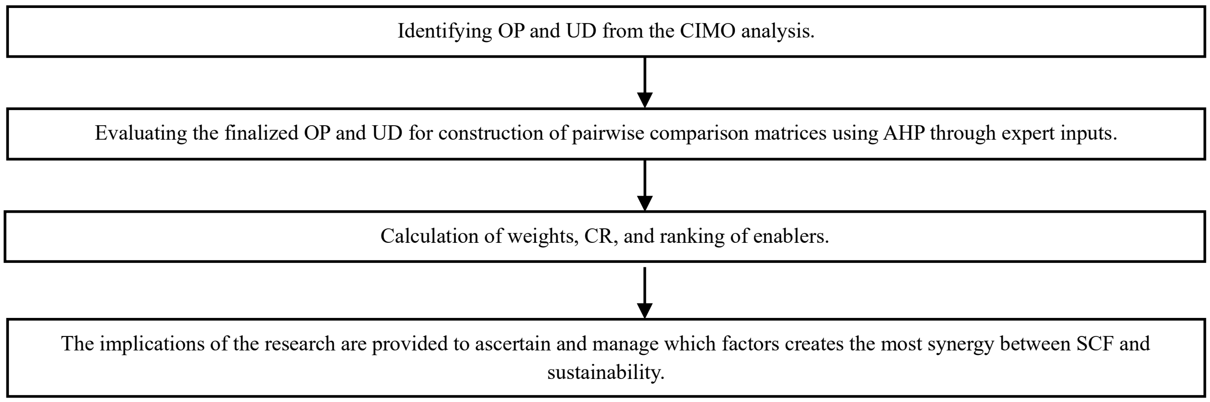


Figure 1. Flow chart of the research work.

Table 4. Scales in pair wise comparisons (Luthra et al., 2016; Saaty, 2008).

Importance intensity	Preference judgments
1	Equally important
3	Moderately important
5	Strongly important
7	Extremely important
9	Extremely more important
2, 4, 6, 8	Intermediate values between adjacent scale values

Table 5. Expert's details.

Profile of experts	Expert A	Expert B	Expert C
Designation	Senior Manager	Assistant Professor	Associate Professor
Sector	Industry-SCM	Academic- SCM, Machine Learning, Data Science, Data-Driven Decision-Making	Academic- Operations and Supply Chain Management
Experience	10 years	4.5 years	12 years

4. Results and Analysis

The purpose was to prioritize the OP and UD that create the most synergy among SCF and sustainability. The following purpose is attained with the help of AHP analysis, below are the results obtained.

4.1 Organizational Practices

The AHP analysis produced the final priority weights and ranking of all evaluated criteria based on the aggregated judgments from the expert panel. The results indicate that **'**Integration of sustainability principles into SCF**'** and 'Instrumental, interconnected and intelligent SC' holds the highest relative importance, demonstrating its dominant influence on the decision context, followed by **'**Flexible SC strategies**'**, while 'Purchasing strategy/ practices' emerged as the least critical criterion. The CR for the aggregated matrix remained within the acceptable threshold, confirming that the expert comparisons were logically consistent and statistically reliable. Overall, the derived weights establish a clear hierarchy of priorities and provide a structured basis for interpreting how each factor contributes to creating the most synergy between SCF and SCS. **Figure 2** shows the pairwise comparison matrix constructed through the AHP technique to assess OP. It includes the weight of each practice, which indicates their level of importance. The normalized principal eigenvector gives the weights derived from the evaluation by the experts. High weights imply that the Organizational Practices have a lot of influence on SCF and SCS. **Table 6** presents the CR and eigenvalue to assess the reliability and consistency of expert judgments for OP. The **Figure 3** presents the priority weights of OP based on the AHP method results. The bar graph helps to visually compare the importance of different OP in terms of their priorities.

The pairwise comparison matrices from the experts were combined using the weighted geometric mean method with the help of the AHP tool Goepel (2018). This method is commonly used to combine multiple expert judgments in AHP. The consistency of the results was checked using the CR, to achieve better consistency, the CR value should be less than 0.10 (Luthra et al., 2016). Geometric Consistency Index (GCI) is (0.18) and the obtained CR value (0.05) is below the acceptable limit of 0.10, indicating that the expert judgments are consistent and reliable.

Matrix		Lean Just-in-time (JIT) practices	Collaborative planning, forecasting and replenishment (CPFR) and	Green purchasing strategies	Purchasing strategy/ practices	Environmental audit of suppliers	Strengthening the supplier relationship	Instrumental, interconnected and intelligent SC	Flexible SC strategies	Integration of sustainability principles into SCF	Normalized Principal Eigenvector
		1	2	3	4	5	6	7	8	9	
Lean Just-in-time (JIT) practices	1	1	1 3/5	2 5/8	3 5/8	5/8	3/5	1/7	1/6	1/7	6.00%
Collaborative planning, forecasting and replenishment (CPFR) and	2	5/8	1	2	3	2/3	5/8	1/6	2/9	1/6	5.24%
Green purchasing strategies	3	3/8	1/2	1	2	2/3	2/3	2/9	2/7	1/5	4.36%
Purchasing strategy/ practices	4	2/7	1/3	1/2	1	3/5	5/8	1/5	2/9	1/6	3.24%
Environmental audit of suppliers	5	1 3/5	1 4/9	1 4/9	1 2/3	1	2 2/7	1/3	3/7	2/5	8.29%
Strengthening the supplier relationship	6	1 5/7	1 3/5	1 4/9	1 3/5	3/7	1	3/8	5/8	5/9	7.83%
Instrumental, interconnected and intelligent SC	7	6 2/3	5 2/3	4 2/3	5 1/3	3 1/3	2 5/8	1	7/8	1	22.72%
Flexible SC strategies	8	5 2/3	4 2/3	3 5/8	4 2/3	2 2/7	1 3/5	1 1/7	1	5/8	18.82%
Integration of sustainability principles into SCF	9	7	6	5	6	2 1/2	1 4/5	1	1 3/5	1	23.49%

Figure 2. Pairwise comparison matrix of OP and corresponding normalized principal eigenvector weights derived using AHP.

Table 6. Organizational practices results table.

Eigenvalue (λ)	GCI	CR
9.574	0.18	0.05

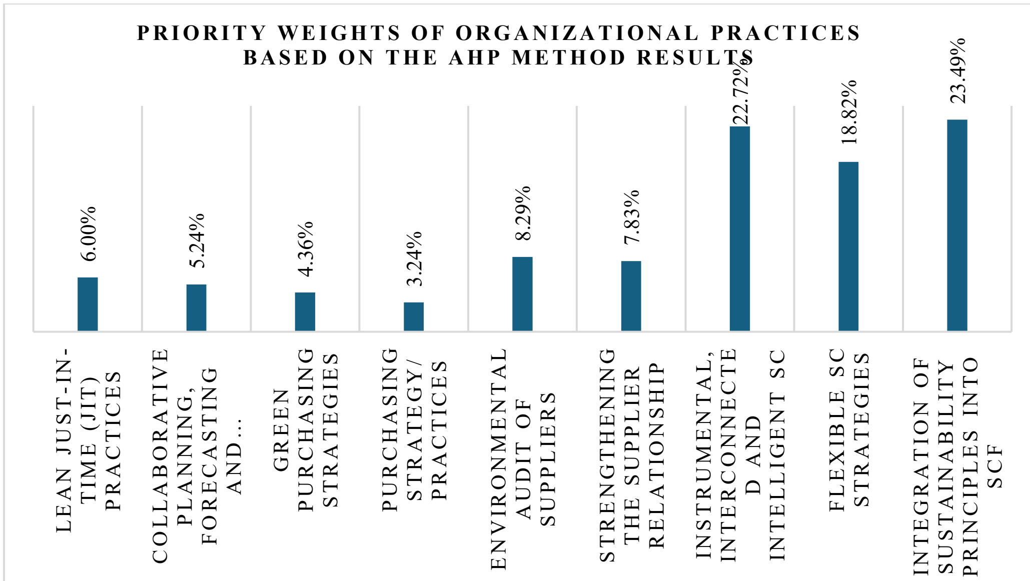


Figure 3. Priority weights of organizational practices based on the AHP method results.

The high importance of factors such as ‘Integration of sustainability principles into SCF’, ‘Instrumental, interconnected and intelligent SC’ and **‘**Flexible SC strategies**’** in the pharmaceutical sector aligns with prior literature. Studies discuss that green SC integration promotes sustainable performance by enabling collaboration across SC partners and removing organizational barriers (Li and Thurasamy, 2025). Prior research also emphasize that pharmaceutical SC increasingly rely on sustainable and agile operational systems to adapt to uncertain environments, with digital transformation further enhances sustainable SC performance in the said sector (Ma et al., 2023). Further, literature emphasized the role of digital technologies in fostering SC operations. Digital transformation enhances SC performance through real-time information sharing, improved visibility, and data-driven decision-making across supply networks (Ma et al., 2023; Shashi, 2023). I4.0 technologies further enable interconnected SC systems characterized by real-time monitoring and predictive analytics (Ivanov and Dolgui, 2021). Studies highlight that flexibility and agility enables firms to adapt to unpredictable circumstances and maintain operational continuity (Shashi, 2023). Pharmaceutical firms in Jordan for example, can offer new products and undertake swift adjustments without incurring severe transition penalties or significant changes in performance outcomes (Al-Hawary et al., 2017).

4.2 Underlying Drivers

The AHP analysis produced the final priority weights and ranking of all evaluated criteria based on the aggregated judgments from the expert panel. The results indicate that ‘Transparency, Traceability and Visibility’ holds the highest relative importance, demonstrating its dominant influence on the decision context, followed by ‘Technological changes/ adoption’, ‘Resilience’, ‘Agility and Responsiveness’ while ‘Innovativeness’ emerged as the least critical criterion. The CR for the aggregated matrix remained within the acceptable threshold, confirming that the expert comparisons were logically consistent and statistically reliable. Overall, the derived weights establish a clear hierarchy of priorities and provide a structured basis for interpreting how each factor contributes to creating the most synergy between SCF and sustainability. **Figure 4** shows the pairwise comparison matrix for the key drivers analyzed through the AHP technique. The matrix reveals the degree of importance given to the key drivers by the experts. The normalized principal eigenvector gives the priority weights, which show the impact of each driver in improving the flexibility and sustainability of the SC. **Table 7** presents the CR and eigenvalue to assess the reliability and consistency of expert judgments for UD. **Figure 5** shows the AHP-derived priority weights of UD, with error bars indicating variability in expert judgments for clearer comparison and interpretation.

The pairwise comparison matrices for the UD were aggregated using the weighted geometric mean method using the AHP tool Goepel (2018). The consistency of the aggregated matrix was evaluated using the CR. The resulting GCI is (0.21) and CR value (0.06) is within the acceptable threshold ($CR \leq 0.10$), confirming the reliability of the expert judgments.

Matrix		Agility and Responsiveness (1)	Transparency, Traceability and Visibility (2)	Resilience (3)	Innovativeness (4)	Technological changes/ adoption (5)	Adaptability (6)	Collaborative knowledge creation (7)	Demand forecasting (8)	Normalized Principal Eigenvector
Agility and Responsiveness	1	1	1/4	3/8	5 2/3	1/4	2 2/7	4	3 5/8	11.04%
Transparency, Traceability	2	4	1	2 5/8	6 1/3	4/5	5 1/3	6 1/3	4 1/3	27.30%
Resilience	3	2 5/8	3/8	1	5	3/5	3 5/8	5 2/3	3 1/3	17.22%
Innovativeness	4	1/6	1/6	1/5	1	1/6	1/3	1/3	1/4	2.52%
Technological changes/	5	4	1 1/4	1 2/3	5 2/3	1	4 2/3	6 1/4	4 2/3	26.29%
Adaptability	6	3/7	1/5	2/7	3	2/9	1	3	2	6.57%
Collaborative knowledge	7	1/4	1/6	1/6	3 1/3	1/6	1/3	1	1/2	3.65%
Demand forecasting	8	2/7	1/4	1/3	4	2/9	1/2	2	1	5.41%

Figure 4. Pairwise comparison matrix of UD and corresponding normalized principal eigenvector weights derived using AHP.

Table 7. Underlying drivers results table.

Eigenvalue (λ)	GCI	CR
8.560	0.21	0.06

The relevance of 'Transparency, Traceability and Visibility' in pharma sector is widely recognized in prior studies. Digital technologies enable improved information sharing and traceability. Traceability systems can effectively adapt to the deployment of medical supplies resulting from unanticipated events in the pharmaceutical and health sectors, boosting the pharmaceutical SC's flexibility and agility (Ma et al., 2023). BCT can track pharmaceutical raw materials and finished products from manufacturing to end-users, providing transparency and detecting fake drugs in the SC by allowing participants to verify data authenticity (Mackey and Nayyar, 2017). The significance of resilience, agility and responsiveness in pharmaceutical SC has been widely emphasized in literature. Pharmaceutical SC has to develop resilient capabilities to face disruptions and maintain the availability of critical medical supplies, especially during crisis like pandemic (Queiroz et al., 2022). Additionally, agile and responsive SCs enable firms to adapt quickly to demand fluctuations and environmental uncertainty (Shashi, 2023).

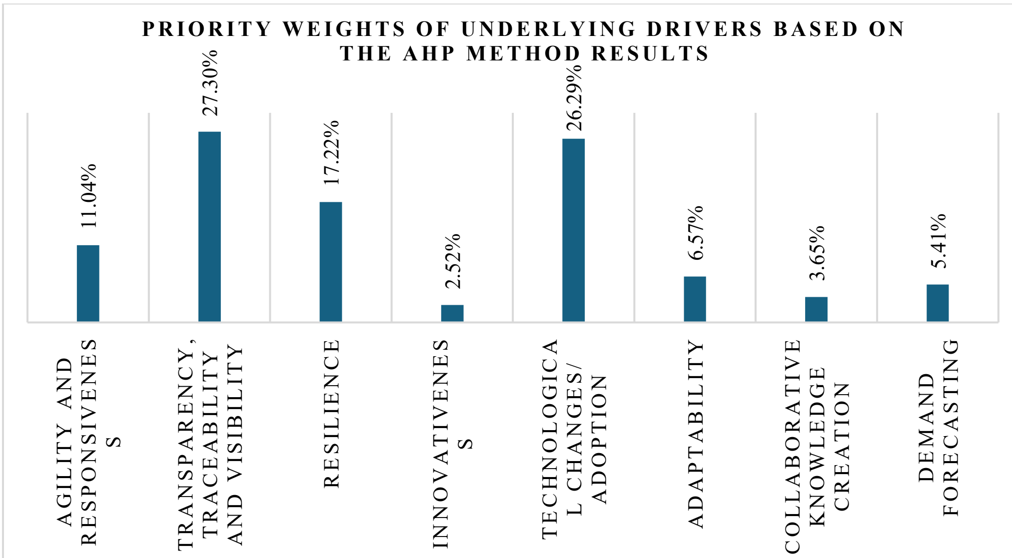


Figure 5. Priority weights of underlying drivers based on the AHP method results.

4.3 Sensitivity Analysis

The sensitivity analysis of the top ranked three OP and UD is carried out by varying weights by +10% and -10% and then recalculating their normalized values. The results highlight that these factors remain largely stable, even after these changes. Although minor changes in ranking were observed between closely weighted factors such as ‘Transparency, Traceability and Visibility’ and ‘Technological changes/adoption’. The overall structure of the results did not change. This indicate that the findings are robust and not highly sensitive to small variations in expert judgements hence the identified key factors can be considered reliable for decision making. **Table 8** shows the sensitivity analysis results, demonstrating the stability and robustness of the derived priority weights under variations in input judgments.

Table 8. Sensitivity analysis results table for OP and UD.

Organizational practices					
Factor	**Original Weight**	**+10%**	**-10%**	**+10% Normalized**	**-10% Normalized**
Instrumental, interconnected and intelligent SC	22.72	24.99	20.45	0.23	0.23
Flexible SC strategies	18.82	20.70	16.94	0.19	0.19
Integration of sustainability principles into SCF	23.49	25.84	21.14	0.23	0.23
Underlying Drivers					
Factor	**Original Weight**	**+10%**	**-10%**	**+10% Normalized**	**-10% Normalized**
Transparency, Traceability and Visibility	27.30	30.03	24.57	0.27	0.27
Resilience	17.22	18.94	15.50	0.17	0.17
Technological changes/adoption	26.29	28.92	23.66	0.26	0.26

A summary of computational steps is provided in **Appendix A**. It outlines the computational procedure adopted for the AHP analysis. Steps: 1- 3 correspond to input preparation, Steps: 4- 6 involve the processing and derivation of weights, and Steps: 7- 8 present the final outputs in terms of priority weights and rankings.

5. Discussion

The first research objective i.e. to identify OP and UD that create synergy between SCF and SCS has been addressed through the CIMO table that presents the OP and UD that create synergy between the two. Further

Table 2 and **3** presents the detailed explanation of identified factors. Then to address the second research objective i.e. to prioritize the identified practices and drivers to determine which factors have the greatest impact on the synergy has been addressed through the AHP based prioritization. We get to the conclusion that OP such as **'**Integration of sustainability principles into SCF**'** and 'Instrumental, interconnected and intelligent SC' holds the highest relative importance, demonstrating its dominant influence on the decision context and UD such as 'Transparency, Traceability and Visibility' holds the highest relative importance, demonstrating its dominant influence on the decision context, followed by 'Technological changes/ adoption' and 'Resilience' have the highest impact on achieving simultaneous improvements in flexibility and sustainability. Digital transformation in the pharmaceutical SC improves information sharing and traceability, promoting sustainable development in the sector. Traceability in SCM has a direct impact on sustainable supply performance. It can also serve as a mediator to increase the positive impact of digital transformation (Ma et al., 2023). Adoption of BCT for track-and-trace is critical for end-to-end traceability, which improves patient safety and long-term SC resilience (Sim et al., 2022). Success Factors for Ideal Traceability includes Visibility and transparency having a substantial impact on overcoming the challenges of creating a safe pharmaceutical SC (Haji et al., 2021). Companies are improving SC security management through information sharing and traceability systems, and they are increasingly emphasizing the role of digital transformation as a driver of sustainable development (Ma et al., 2023).

The prioritized factors hold substantial strategic importance within the pharmaceutical sector, as they directly influence operational robustness, regulatory compliance, and long-term competitive performance. The major risk factors are the unavailability of medicine due to unanticipated demand and the lack of specialized or alternative drugs, nevertheless, these risks could be addressed by digital technology. These supply shortfall concerns can be met with a suitable digital technology infrastructure that includes BDA and BCT. Organizations can strengthen their supply networks by tackling risk factors through the deployment of a digitalized SC. This fosters resilience and efficiency (Wong et al., 2023). The study shows that agile and flexible SC strategies significantly reduce drug shortages and inventory waste, demonstrating that operational flexibility directly improves sustainability performance (Hamzehlou, 2024). The demand for pharmaceuticals is growing, and the company needs to include its suppliers. Manufacturing businesses will benefit from increased agility and resilience as a result of supplier integration. The organization optimizes planning by collaborating with SC partners. Supplier involvement will give a swift response in providing raw ingredients for pharmaceutical businesses (Siagian et al., 2021).

Digital technology improves SC processes while automating routine tasks. This reduces the risk of human error and response time, allowing firms to adjust and optimize SC utilization of resources with greater flexibility (Li and Thurasamy, 2025). Improving SC resilience within pharmaceutical distribution networks enhances overall network resilience (Bastani et al., 2021). The demand for pharma products is growing and the company must now include its suppliers. Integration between organizations and suppliers will give agility and resilience to manufacturing companies (Siagian et al., 2021). Flexibility is characterized as agility, which indicates the firm's capacity to adjust to unpredictable global business settings. The agile SC enables pharmaceutical firms to ensure a more rapid and continuous flow of products and services across the SC. Agility also contributes to predictability by minimizing overall lead time through the detection and rapid response to changes (Shashi, 2023). SC visibility, flexibility, adaptability and agility are critical factors that support the four stages of SC resilience preparation, reaction, and recovery. This is to keep the complex pharmaceutical SC stable in the face of unpredictable events (Ma et al., 2023). The adaptability of a medical SC refers to its ability to respond rapidly and efficiently to changing circumstances, such as fluctuations in demand, disruptions, regulatory updates, or technological advances. This ensures that important medical products are still available and that the SC can function in unforeseen circumstances (Momena et al., 2025).

Flexibility and sustainability work together by helping SCs adapt responsibly, and technology makes this possible through real-time data, transparency, and smarter decisions.

The study contributes to SCF literature by providing a structured prioritization of key factors contributing to synergy between SCF and SCS in the pharmaceutical sector.

First, the finding extends the existing theoretical discussion on DCV by discussing SCF and SCS as capabilities and how synergy between them leads to improved performance in a highly regulated pharma sector. These capabilities facilitate firms to sense environmental changes and adapt to changing business environment by combining internal SCF capability with external SC agility thereby strengthening the theoretical understanding of flexibility as a dynamic capability within healthcare and pharmaceutical contexts.

Second, the study adds to the literature on digital and intelligent SC by highlighting the growing importance of technology adoption as well as 'instrumental, interconnected, and intelligent' SC. By prioritizing these factors, the study provides empirical support for emerging theoretical arguments that digital technologies play a critical role in enabling real-time information sharing, enhanced visibility, and adaptive decision-making within complex supply networks.

And lastly, it contributes to the literature specific to SCS by discussing the growing significance of integrating sustainability principles into SC.

The study can contribute to providing managerial implication given the high priority assigned to 'Transparency, Traceability, And Visibility', managers must consider strengthening track-and-trace systems, enhance real-time information sharing with SC partners, and implement digital monitoring mechanisms. These practices are particularly important in pharmaceutical SC where regulatory compliance, product integrity, and counterfeit drug prevention are critical. The importance of 'resilience, agility, and responsiveness' suggest that firms must develop flexible strategies to manage disruptions. Managers can achieve this by diversifying supplier bases, maintaining strategic inventory buffers, and improving collaboration with logistics providers and contract manufacturers.

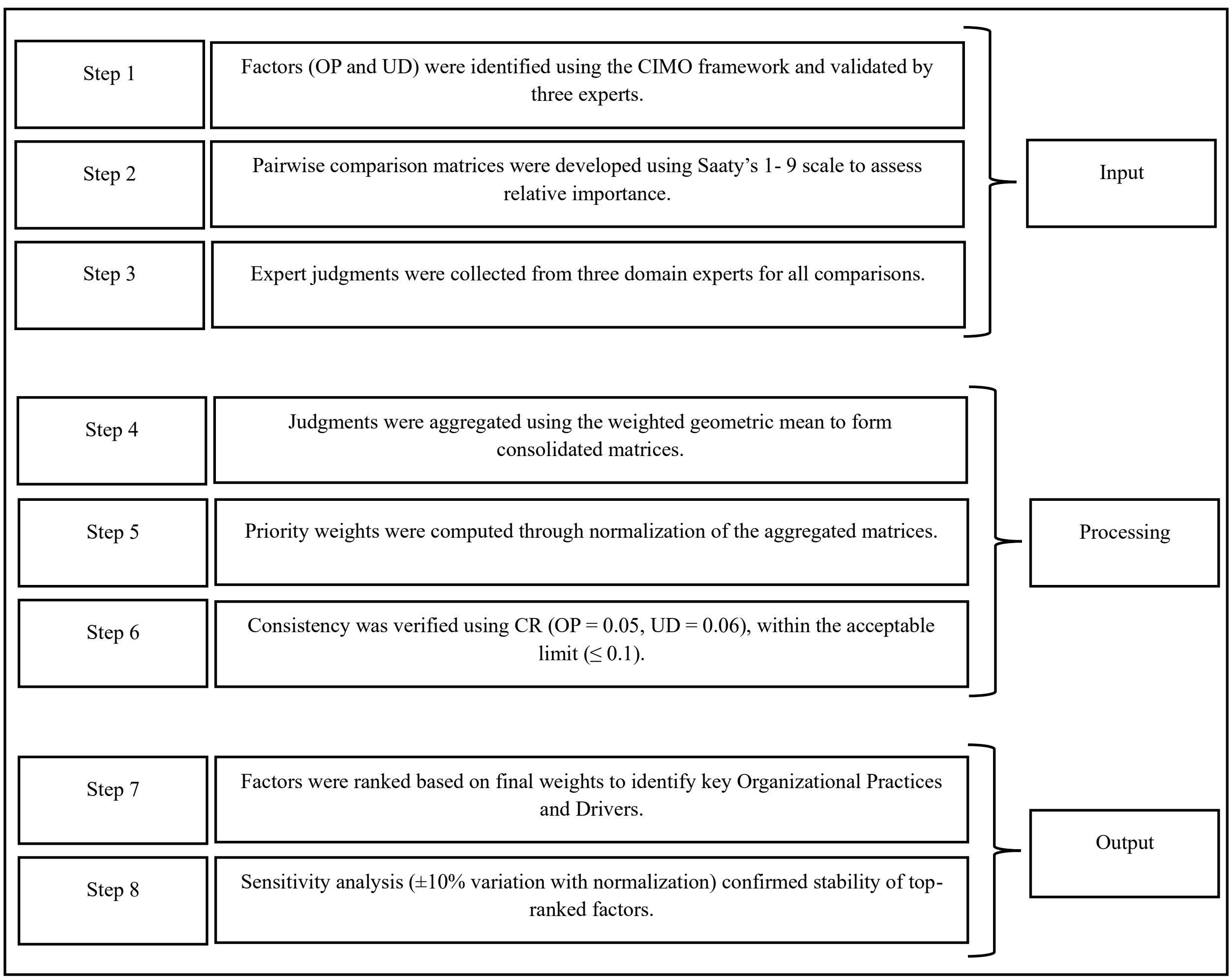
The prioritization of technological changes and adoption and the development of 'instrumental, interconnected, and intelligent' SC highlights the need for digital transformation. Pharmaceutical firms should invest in digital technologies such as advanced analytics, blockchain-based systems, and integrated SC platforms to enhance visibility and decision-making. And integrating 'sustainability principles into SCF initiatives' requires managers to incorporate environmentally responsible sourcing, efficient logistics planning, and sustainable packaging solutions, enabling pharmaceutical firms to balance regulatory compliance, operational efficiency, and long-term sustainability objectives.

6. Conclusion

This study employs CIMO analysis to identify and AHP to prioritize the OP and UD that creates synergy between SCF and sustainability. The results highlight that practices integrating sustainability principles along with instrumented, interconnected and intelligent SC systems hold highest relative importance. Among the UDs, transparency, traceability and visibility emerge as the most influential followed by technological adoption and resilience. The results of our study shows that some practices and drivers are more relevant than others, this can facilitate managers with actionable insights on which high priority factor warrant investment to maximize both SCF and sustainability. Since integrating sustainability practices ranked the highest, firms should combine sustainability aspects with flexible SC operations in order to get the most efficient output. Further we understand that there are various digital interventions that contributes in the synergy between SCF and sustainability hence investing in integrated digital systems that are instrumented and interconnected will lead to higher advantages. Visibility and traceability must be strengthened as improving real-time data sharing and end to end visibility contribute in improving both flexibility and sustainability. Digital adoption and resilience planning are essential for achieving stable and sustainable operations in dynamic market conditions. Further it facilitates strategic allocation of resources toward practices and drivers that have the greatest practical impact, enabling pharmaceutical firms to strengthen responsiveness, adaptability, and sustainable performance simultaneously.

The limitations of the study include that AHP depends on expert judgement which may reflect perception and may differ with another panel of experts. Further our findings are specific to the pharmaceutical sector and cannot be assumed to be acceptable by other industries and this study provides priorities but does not test whether high ranked enablers actually improve performance in practice. Future studies can use other methods like ISM or DEMATEL to map causal links between the factors, studies may include empirical validation of the prioritized factors, application of hybrid decision-making methods, and cross-sector comparative studies.

Appendix A. Summary of Computational Steps



Conflicts of Interest
The authors confirm that there is no conflict of interest to declare for this publication.

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AI Disclosure
During the preparation of this work the author(s) used generative AI in order to improve the language of the article. After this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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