Developing pharmaceutical supply chain resilient capabilities: the role of Industry 4.0 technologies

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Abstract

Purpose – The purpose of this study is to advance understanding of how PSCs can re-imagined, re-designed and strengthened by leveraging industry 4.0 (I4.0) technologies. Building resilience in Pharmaceutical Supply Chains (PSCs) has become imperative in the wake of COVID-19 and other global disruptions.

Design/methodology/approach – This study adopted a qualitative approach using thematic analysis and the Gioia method on a corpus of data from 114 articles published in 84 peer-reviewed academic journals. The authors conducted a problematising review to critically analyse the contributions of I4.0 technologies to PSCs and demonstrate the distinctiveness of PSC resilience.

Findings – The thematic analysis revealed the advantages and barriers to I4.0 implementation in PSCs, emphasising on how these technologies support sensing, seizing and reconfiguring capabilities. Drawing on dynamic capability theory, this study proposes the pharmaceutical supply chain resilient capabilities (PSCRC) model, which conceptualises the capability building required to withstand and adapt to disruption.

Originality/value – The authors argue that the PSCRC model provides i) a theoretical contribution by clarifying the micro foundations of resilience, and ii) a practical roadmap for supply chain leaders seeking to deploy I4.0 technologies to coordinate processes, secure materials and build sustainable and adaptive PSCs. The paper also outlines future research avenues to advance scholarly and managerial understanding of PSC resilience.

Keywords Industry 4.0 technology, Pharmaceutical supply chain, Disruption, Resilience, Systematic literature review

Paper type Research paper

1. Introduction

The necessity of a digital future, amplified by the COVID-19 disruption and more recently by the "black swan" crisis (Enz *et al.*, 2024), has spurred the implementation of Industry 4.0 technologies (I4.0) (Frederico *et al.*, 2023; Kumar *et al.*, 2021). Manufacturing and service organisations adopt digital technologies to reshape entire business models, create value, facilitate real-time informed decision-making, save time and money (Cranmer *et al.*, 2022). I4.0 technologies, such as big data analytics (BDA), Internet of Things (IoT), artificial intelligence (AI) and blockchain enhance sensing capabilities by improving real-time visibility; seizing capabilities by enabling data-driven decision-making; and transforming capabilities by facilitating agile reconfiguration of supply chains in response to disruptions. These capabilities are valuable assets that support organisations and supply chains in responding quickly and efficiently to a crisis (Cadden *et al.*, 2022).

In the healthcare sector, the adoption of technologies to analyse large amounts of data to extract pertinent knowledge and valuable insights has also increased. The healthcare data analytics market was valued at \$43.1bn in 2023 and is expected to grow by 21.1% from 2024 to 2030 (Grand View Research, 2023). Implementing technologies in the healthcare sector contributes toward more accurate medical diagnoses, precise prescriptions, drug and vaccine development (Chen *et al.*, 2023)

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as well as great advances in managing pharmaceutical supply chains (PSCs). However, PSCs must deal with financial, communication, waste and complexity challenges (Papalexi *et al.*, 2020; Papalexi *et al.*, 2022). Recent global events, such as the pandemic, wars and natural disasters have highlighted the severity of these pre-existing challenges.

Although scholarly articles have highlighted the positive impact of deploying I4.0 technologies on optimising organisational performance (Alharthi *et al.*, 2020; Ali *et al.*, 2022; Cadden *et al.*, 2022; Kandasamy *et al.*, 2025), there remains a gap in understanding how these technologies collectively foster resilience by shaping dynamic capabilities (Bapatla *et al.*, 2023). In addition, Yaroson *et al.* (2021) highlighted that although resilience has been extensively discussed in supply chain literature, there is a limited focus on resilience strategies in PSCs. In the healthcare sector and PSCs, the resilience and sustainability agendas driven by CEOs and senior managers have accelerated the pace of I4.0 technology adoptions (Raj *et al.*, 2022), which supports the rationale and significance of this study. Successful development of a resilient supply chain system requires orchestrating resources and developing integrated trusted systems to enable increased data sharing and enhanced communication (Aslam *et al.*, 2023; Babu *et al.*, 2022). This is a more complex process than might have been assumed but developing supply chain capabilities by combining tangible (e.g. investing in I4.0 technologies), intangible (e.g. organisational learning and cultural capability development) and human resources (e.g. management capability development) could potentially ease this complexity and create robust PSCs (Cadden *et al.*, 2022).

Therefore, this research investigates the role of I4.0 technologies in shaping the dynamic capabilities that underpin pharmaceutical supply chain resilient capabilities (PSCRC), enabling PSCs to anticipate, adapt to, and transform in response to future disruptions. Specifically, in this study, we define pharmaceutical supply chain resilience as the capability of PSCs to anticipate, withstand, and recover from disruptions such as active pharmaceutical ingredient (API) shortages, regulatory interventions, counterfeit drug infiltration and cold chain failures, while safeguarding patient safety and maintaining trust. To achieve the study's objectives, we adopt dynamic capability theory (DCT) as a lens to conceptualise how PSCs sense, seize and reconfigure resources to develop resilient capabilities. DCT provides a structured framework to investigate how PSCs can leverage I4.0 technologies for long-term adaptability and resilience (Malakar *et al.*, 2025). Although DCT has been widely adopted across supply chain studies, its operationalisation has often remained abstract, with limited attempts to specify how sensing, seizing and reconfiguring happen in practice (Roh *et al.*, 2022; Mikalef *et al.*, 2020). This is observed in the pharmaceutical sector, where resilience involves unique dynamics as previously mentioned. By explicitly mapping I4.0 technologies onto Teece's (2007) micro foundations (the distinct skills, processes, procedures, organisational structures, decision rules and disciplines, which undergird enterprise-level sensing, seizing and reconfiguring capacities), our study offers a sector-specific operationalisation of DCT, moving beyond the traditional primary data analysis that can be found in the literature (Yaroson *et al.*, 2023, 2024).

Therefore, we have developed the following research question to structure the study:

RQ1. How do Industry 4.0 technologies shape the development of sensing, seizing and reconfiguring capabilities that enhance pharmaceutical supply chain resilience?

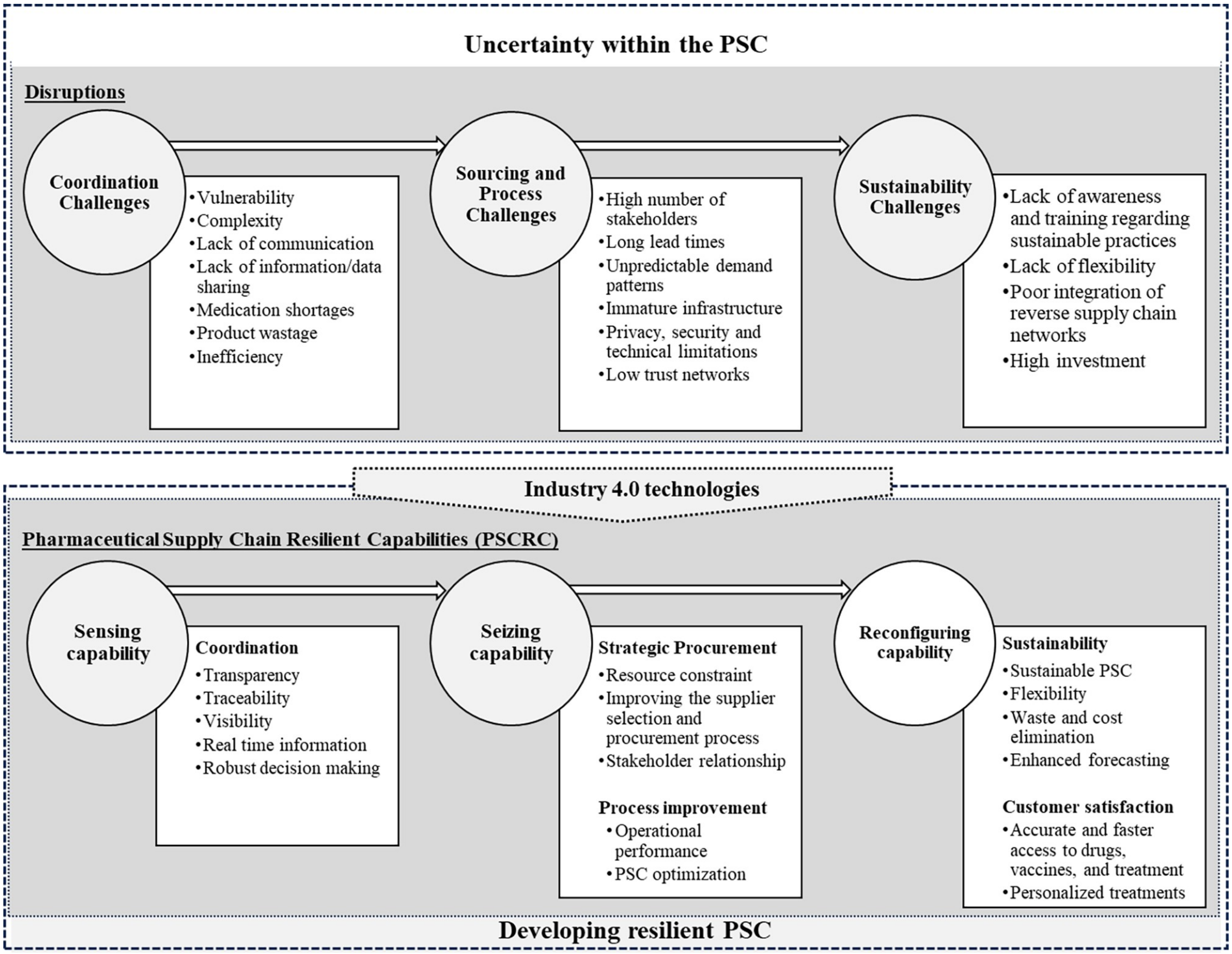
Existing research on Industry 4.0 in PSCs reveals relevant aspects. First, many studies adopt a fragmented, single-technology perspective (e.g. blockchain for traceability), overlooking interoperability across I4.0 systems (Wu *et al.*, 2023; Nguyen *et al.*, 2022; Uddin *et al.*, 2021). Moreover, resilience and sustainability are frequently treated as separate goals, despite evidence that I4.0 technologies can simultaneously enhance recovery and reduce waste (Jraisat *et al.*, 2023; Ma *et al.*, 2023). These issues highlight the need for a holistic framework that integrates I4.0 technologies, operationalises DCT micro foundations, and addresses the unique vulnerabilities of PSCs in a post-pandemic context.

The proposed PSCRC conceptual model (Figure 1) can be used to guide researchers and practitioners in assessing PSC resilience capabilities. The outputs of the structured literature review (SLR) and inductive qualitative research approach helped us develop the PSCRC model. It represents the contribution of I4.0 technologies to the PSC dynamic capability-building process that allows resilient PSC creation while extending the dynamic capability view. The conceptualisation of the model is discussed throughout the paper and specifically in the findings section.

The contributions of this study are threefold:

1 Our review is the first to holistically assess the contribution of I4.0 technologies within the PSC to achieve resilience and critically evaluates, conceptualises, and problematises existing knowledge by thematically analysing the selected articles. This approach aims to generate new ways of understanding a given area of concern (Gruner and Minunno, 2024; Breslin and Gatrell, 2020). A handful of previous studies on the implementation of I4.0 technologies within the PSC (Chen *et al.*, 2023; Khan *et al.*, 2023b) took a narrow view of single I4.0 technology adoption (e.g. the adoption of AI) to achieve the overall performance (Cadden *et al.*, 2022).
2 This study adopts a DCT lens to review the PSC literature to explore the effect of applying I4.0 technologies within it, particularly the contribution of those technologies to develop a resilient PSC capable of dealing with future challenges. This is achieved through juxta-positioning of the literature referring to the adoption of I4.0 within the PSC. Our review is among the first to operationalise Teece's (2007) DCs micro foundations within the PSC by developing the PSCRC model. This provides clarity regarding the construct of capabilities, which is an element that is missing in the DCT literature (Bruyaka *et al.*, 2024 Pitelis,2022).
3 The emergent PSCRC model and the discussed future research avenues provide potential constructs for laying the groundwork for case studies and empirical research, resulting in future theoretical developments. DCT

Figure 1 The pharmaceutical supply chain resilient capabilities (PSCRC) model



literature highlights that quantitative studies that operationalise and measure organisational capabilities are underdeveloped (Cronin and George, 2023; Schilke *et al.*, 2018).

The remainder of this paper is organised as follows. The next section outlines the background and motivation for this study. Section 3 discusses the methodology of the research, with details about how the data are collected and analysed in the exploratory study. In Section 4, the results and thematic map are discussed by theorising the literature related to PSCs and the use of technology within it. This section provides insights into the existing relevant knowledge and presents the PSCRC model. Section 5 discusses the results, and Section 6 concludes the paper by presenting a research agenda and key avenues for future research.

2. Literature review: background and motivation

2.1 PSCs within an uncertain context

According to Pettit *et al.* (2019), resilience is often defined as the ability to recover in a timely and cost-effective manner and return to its initial state after a crisis. However, recently, resilience has been associated with the capacity to bounce back further by adapting and growing as a result. Flexibility, visibility and collaborative practices contribute towards resilience (Kamalahmadi *et al.*, 2022; Yaroson *et al.*, 2024). The COVID-19 pandemic has exposed vulnerabilities in global PSCs, causing disruptions that affect access to critical medicines and lead to shortages of drugs, active pharmaceutical ingredients (APIs) and medical supplies (Khan *et al.*, 2023a). In fact, from the perspective of the collective society, the pandemic has more significantly highlighted the need for building resilience capabilities (Paul *et al.*, 2023).

Developing resilience capabilities may be challenging for the PSC due to its unique nature, characterised by high complexity, lack of transparency, inefficiencies in the production process, long lead times, cost intensity, limited suppliers and difficulties in tracking and tracing products, as Papalexi *et al.* (2020) and Yaroson *et al.* (2023) explained. In addition, the industry needs to adhere to strict regulations and compliance and manage the risks of counterfeit drugs (Bapatla *et al.*, 2023). PSCs are also vulnerable to geopolitical events and natural disasters (Enz *et al.*, 2024). Therefore, in this uncertain global context, rethinking and redesigning PSC has become a key priority. Multiple strategies have been adopted to achieve supply chain resilience, including inventory and capacity buffers (Wong *et al.*, 2020); multi-sourcing strategies; and near-shoring approaches (Kano and Oh, 2020). Naz *et al.* (2022) explained that PSCs can build resilience capabilities by managing risk proactively, enhancing their level of preparedness, diversifying sourcing for raw materials and APIs, reshoring manufacturing plants, and investing in digital technologies. Indeed, Yaroson *et al.* (2023) categorised the capabilities required to build PSC resilience into two types: proactive capabilities, which anticipate disruptions, and reactive capabilities, which are employed after disruptions occur (Kamalahmadi *et al.*, 2022). Key enablers of resilience within the PSC include flexibility, visibility, and collaboration (Yaroson *et al.*, 2021; Ozdemir *et al.*, 2022). However, as highlighted by Yaroson *et al.* (2021, 2023, 2024) the development of resilience within PSCs remains limited and fragmented. Table 1 presents a summary of PSC related studies that have adopted I4.0 technologies, along with the specific resilience capabilities they targeted.

2.2 Digital transformation and I4.0 technologies within the pharmaceutical supply chain

Technologies such as AI, BDA, IoT, blockchain, robotics and virtual and augmented reality offer huge benefits to the healthcare and pharmaceutical sectors to achieve more accurate and faster diagnoses and treatments, development of new drugs and vaccines, as well as enhanced access to clinicians and medicines (Trenfield *et al.*, 2022). Moreover, the adoption of I4.0 technologies has emerged as a solution for enhancing PSC traceability, visibility, flexibility, responsiveness, and adaptability within these complex and global networks (Chen *et al.*, 2023). In the literature, we observe different levels of adoption and advancement. Some companies invest in blockchain and the Internet of Things (IoT) to improve product visibility and traceability across the supply chain in real time, whereas others use smart sensors and AI to predict equipment failures, optimise maintenance, and improve inventory management and demand forecasting during disruptive events (Nguyen *et al.*, 2022). Qader *et al.* (2022) examined the impact of I4.0 technologies on supply chain performance and collected data from food, beverage, and pharmaceutical companies, and Saha *et al.* (2022) empirically studied how emerging technologies impact PSCs. Benazzouz and Auhmani (2023) developed a digitalisation maturity model to help PSC partners assess their adoption levels in terms of digitalisation.

Yaroson *et al.* (2024), Jraisat *et al.* (2023), Alharthi *et al.* (2020) and Thakuriya *et al.* (2023) proposed conceptual models for the adoption of blockchain technology to enhance sustainability and effectiveness within the PSC. However, these studies tend to focus on siloed applications, such as hospital operations (Alharthi *et al.*, 2020), counterfeit drugs management (Thakuriya *et al.*, 2023), sustainability initiatives (Jraisat *et al.*, 2023) and addressing medicine shortages (Yaroson *et al.*, 2024). Table 1 provides a summary of key studies that examine the adoption of I4.0 technologies to enhance resilience. As evidenced by the table, the adoption of I4.0 technologies in the PSC literature remains fragmented, with a predominantly static focus on DCT. Therefore, a holistic I4.0 implementation across the entire PSC is needed to support the development of resilient capabilities; an objective that this research aims to address. The uptake of I4.0 technologies is inevitable, and this phenomenon must be studied academically (Chen *et al.*, 2023; Khan *et al.*, 2023b).

2.3 Dynamic capability theory and potential links with I4.0 in PSC

The supply chain literature suggests that the DCT has been adopted to examine the effect of dynamic capabilities on organisational performance in uncertain environments (El Baz and Ruel, 2021). According to Teece (2007), the skills and competencies of sensing, seizing, and reconfiguring are considered the micro foundations that are fundamental determinants of firm performance. These organisational capabilities assist firms in responding to potential risks quickly by identifying changes in the environment (sensing), interpreting the required resources and actions to overcome uncertainties, enacting flexible operations (seizing) and rearranging resources to recover and regain the continuation of operations (reconfiguring). This theory enables the analysis of companies and their SC's ability to reshape structures and systems in response to changes in uncertain business environments and create opportunities (Bruyaka *et al.*, 2024).

Table 1 A summary of key studies examining the adoption of I4.0 technologies to enhance resilience

I4.0 implementation (Corpus references)	PSC studies focus	Resilience capabilities building
Blockchain technology (1,3, 4, 5, 6, 7, 9, 12, 29, 34, 33, 35, 40, 46, 48, 49, 50, 51, 54, 55, 56, 57, 58, 59, 60, 61, 62, 66, 74, 77, 81, 83, 86, 92, 93, 99, 105, 106, 107, 109, 112 104)	Information flow redesign trusted process interoperability sustainability and effectiveness handling complexity poor-quality pharmaceuticals prevention prevent counterfeit, stolen, or contaminated drugs	Transparency visibility traceability collaboration and coordination flexibility and agility accessibility robustness sustainability supply base optimisation privacy and security
Big data analytics Artificial Intelligence Machine learning (4,10, 13, 17, 18, 21, 32, 35, 39, 41, 43, 49, 57, 58, 61, 63, 82, 87, 95, 100, 107, 111)	Organisational performance prediction of disease outbreaks demand forecasts during disruptive events	Sustainability transparency traceability visibility collaboration optimising decision making
Internet-of-Things digital twin (DT) (7, 47, 73, 99, 106)	Increase automation information data scarcity	Transparency collaboration and coordination flexibility accessibility
Additive manufacturing (AM) technologies (52, 94)	Personalised medical devices or drug delivery systems quality improvement	Flexibility sustainability transparency personalisation
Drone (36, 99)	Medicine delivery quality of medicines	Supply base optimisation accessibility

The disruptions generated by COVID-19 and their impact on PSCs and, most importantly, the difficulties in responding to this crisis, highlight the importance of utilising supply chain capabilities to rethink existing PSC resilience capabilities and develop new ones (Mikalef *et al.*, 2020). We believe that the pandemic coupled with the rise of digital technologies marked the beginning of a paradigm shift in the management of supply chains and added to our motivation to study the future of resilience capabilities. By adopting a DCT lens, we can shed light on how PSCs can deploy I4.0 technologies to reconfigure their resources to develop resilience capabilities. We expect the adoption of I4.0 technologies to enable the development of integrative capabilities by enhancing the communication and coordination of PSCs.

Specifically, I4.0 technologies operationalise the micro foundations of DCT: the distinct skills, processes, procedures, organisational structures, decision rules and disciplines, which undergird enterprise-level sensing, seizing and reconfiguring capacities, by enabling data-driven, agile and collaborative responses to disruption. First, I4.0 technologies extend and accelerate sensing capabilities by transforming vast volumes of data into actionable insights, a critical requirement for PSCs where patient safety and regulatory compliance are non-negotiable (Uddin *et al.*, 2021; Musamih *et al.*, 2021). For example, big data analytics (BDA, artificial intelligence (AI) and Internet of Things (IoT) sensors enhance visibility across supply networks, enabling early detection of issues, shortages, and other risks (Bag *et al.*, 2023; Bassiouni *et al.*, 2023). Second, the technologies enhance decision-making speed, trust, and precision, strengthening the seizing capability. For example, blockchain platforms and smart contracts can provide secure, real-time information flows that improve trust among PSC partners, while digital twins and AI-based decision can support systems allow scenario testing and rapid mobilisation of resources during crises (Aloini *et al.*, 2023; Joseph Jerome *et al.*, 2022). Finally, I4.0 technologies enable PSCs to rapidly reconfigure its manufacturing and logistics networks. Additive manufacturing facilitates localised production of critical medicines, robotics and automation enable rapid capacity adjustments, and cloud-based collaboration platforms support flexible supplier switching and process redesign. Collectively, these linkages clarify how I4.0 technologies enact dynamic capabilities in PSCs, bridging the gap between abstract theoretical constructs and actionable resilience-building mechanisms.

Research has underlined the importance of building dynamic capabilities by adopting innovative approaches to respond to risks generated in volatile environments (Cadden *et al.*, 2022), but there is limited information regarding this process within the PSC in the current literature. Although Yaroson *et al.* (2024) adopted the DCT to build resilience within the PSC by enhancing decision-making capabilities to manage medicine shortages, they emphasise the need to move beyond a static application of the DCT and explore its holistic adoption – an approach this research addresses. In addition, our study addresses the call for further research by Roh *et al.* (2022) and Cadden *et al.* (2022) regarding the limited focus on the role of intangible capabilities in creating resilience. Therefore, we have developed a PSCRC model (Figure 1) inspired by the dynamic capability view to explore how I4.0 can support the PSC in employing its capabilities to mitigate future disruptions.

3. Materials and methods

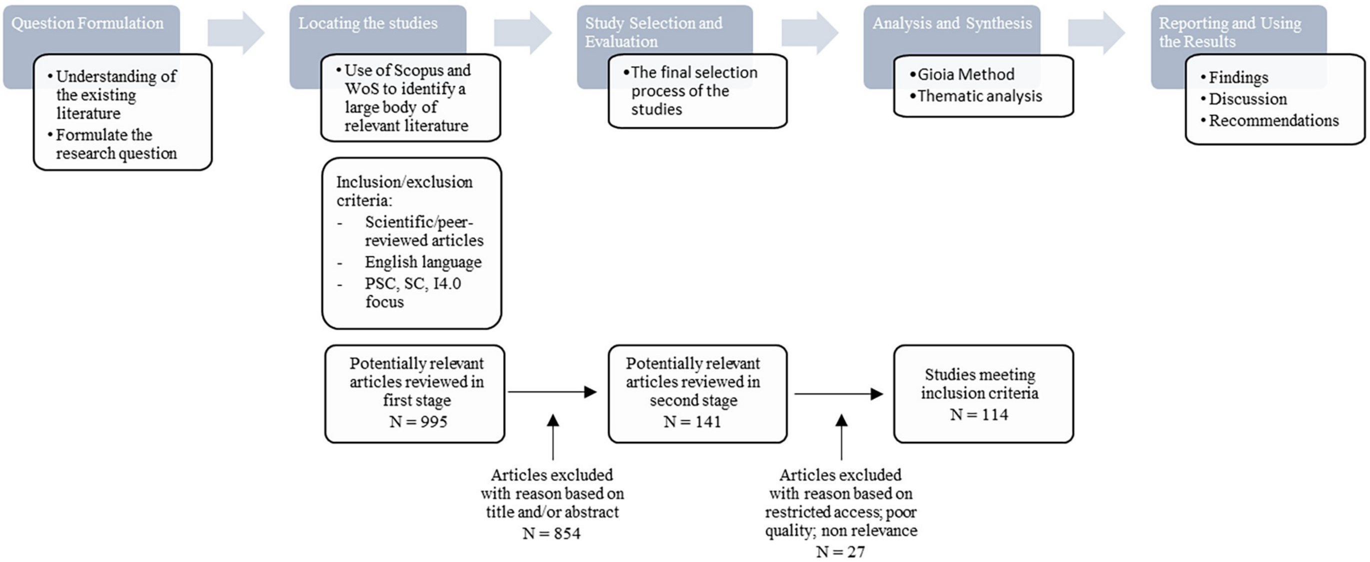
This study adopted an evidence-informed SLR approach to collate the required data for qualitative thematic analysis, following the guidelines suggested by Denyer and Tranfield (2009). The systematic review employed five refinement stages and was conducted in August 2023. A PRISMA-style flow diagram is presented to document the screening process as shown in Figure 2. The screening process is documented in a PRISMA-style flow diagram, which details the identification, screening, eligibility and inclusion stages, ensuring a transparent and replicable process.

First, the SLR aims to identify relevant literature that leads to the formation of a data corpus for further thematic analysis (Wang *et al.*, 2024). Second, a keyword search was conducted using Scopus and Web of Science (WoS), two common databases that provide broad access to a multitude of peer-reviewed studies (Heinis *et al.*, 2022). The search string used for Scopus is as follows: (({Logistics 4.0} OR {Industry 4.0} OR {Supply Chain 4.0} OR {I4.0} OR {ArtificialIntelligence} OR {AI} OR blockchain OR iot OR {InternetofThings} OR cloud OR {CloudComputing} OR {Robots} OR {cobots} OR drones OR {AdditiveManufacturing} OR am OR 3d OR {3Dprinting} OR {CyberPhysicalSystems} OR cps OR bda OR {BigData} OR {Machine Learning} OR ml OR vr OR ar OR {VirtualReality} OR {AugmentedReality} OR {AutonomousVehicles} OR sensors) AND (pharma* OR psc OR drugs OR medicines) AND ({supplychain} OR sc OR scm OR logistics)) AND (LIMITTO (DOCTYPE, "ar")) AND (LIMITTO (LANGUAGE, "English")) AND (EXCLUDE (SUBJAREA, "MEDI") OR EXCLUDE (SUBJAREA, "BIOC") OR EXCLUDE (SUBJAREA, "PHAR") OR EXCLUDE (SUBJAREA, "IMMU")).

The search string utilised for the WoS is as follows: (("Logistics 4.0" OR "Industry 4.0" OR "Supply Chain 4.0" OR "I4.0" OR "Artificial Intelligence" OR "AI" OR blockchain OR iot OR "Internet of Things" OR cloud OR "Cloud Computing" OR "Robots" OR "cobots" OR drones OR "Additive Manufacturing" OR am OR 3d OR "3D printing" OR "Cyber Physical Systems" OR cps OR bda OR "Big Data" OR "Machine Learning" OR ml OR vr OR ar OR "Virtual Reality" OR "Augmented Reality" OR "Autonomous Vehicles" OR sensors) AND (pharma* OR PSC OR drugs OR medicines) AND ("supply chain" OR SC OR SCM OR logistics)).

Furthermore, the inclusion and exclusion search criteria were specified as follows: academic scientific/peer-reviewed articles that focus on PSCs and I4.0 technologies were targeted, and only articles written in English were considered. A total of 1,324 and 505 contributions were identified from Scopus and WoS, respectively. The inclusion/exclusion criteria were gradually applied and studies with noncoherent abstracts and duplicates were removed, leaving 995 unique sources in the data set. To achieve an acceptable level of accuracy when applying the selection criteria, we conducted an additional round of reviews that reduced the total number to 141. Finally, the study selection process was conducted. The authors

Figure 2 PRISMA flow diagram illustrating the SLR process; including identification (1,829 articles from Scopus and WoS) screening (995 articles; removal of duplicates and non-coherent abstracts), eligibility (review of 141 articles) and inclusion (114 articles for thematic and Gioia analyses)



reviewed the titles and abstracts of the 141 articles identified in the previous stage and used colour coding to categorise the articles into three groups: "accepted", "borderline" and "rejected" (Heinis *et al.*, 2022). Based on this process, 27 articles were excluded because of non-relevance (e.g. focus on healthcare and not PSCs), poor quality or restricted access. Finally, 114 articles were included in the SLR (Table 2).

Fourth, the 114 articles were analysed. The analysis consisted of two parts: thematic analysis (Sodhi *et al.*, 2022) and the Gioia method (Williams and Shepherd, 2017) for conceptual development and proposing an emergent model. The thematic analysis aimed to examine articles to identify enablers and challenges in implementing I4.0 technologies in PSCs. We adopted the six steps suggested by Sodhi and Tang (2018) to conduct the thematic analysis: We (1) familiarised ourselves with the corpus of "data"; (2) generated initial codes; (3) searched for themes; (4) reviewed these themes; (5) defined and named these themes, and (6) produced the report. To ensure the reliability of the thematic analysis, we adopted a multi-step approach to enhance rigor. This approach consists of the following three steps: (1) inter-coder reliability: two researchers independently coded a subset of articles to generate initial codes. Disagreements were resolved through discussion and consensus among the research team. (2) peer debriefing: a third researcher, not involved in the initial coding, reviewed the coding framework and emergent themes to ensure consistency and reduce bias. (3) iterative theme refinement: themes were iteratively refined during team meetings, where all authors discussed and validated the themes against the data corpus to ensure thematic saturation. The next part of the analysis involved applying the Gioia method to develop an emergent model. Building on grounded theory principles, the Gioia method employs a central research question to direct qualitative data collection and the subsequent theory development. Applying inductive data structuring methods, such as the Gioia method, enables researchers to uncover the dimensions and their interactions for further empirical and quantitative studies (Williams and Shepherd, 2017).

The Gioia method, traditionally used for primary qualitative data, was adapted to analyse secondary data from 114 peer-reviewed articles following its usage for secondary data has been effectively evidenced in domains such as social network analysis (SNA) (Williams and Shepherd, 2017) and tourism (Jiménez-Partearroyo *et al.*, 2024). Unlike interview-based applications, we coded textual data from article findings to identify first-order concepts, second-order themes and aggregate dimensions. To mitigate bias, we used a structured coding protocol, and triangulated findings across multiple sources to address potential biases during team discussions.

Finally, the SLR outputs were reported. The findings constitute the following: (1) thematic analysis discovers enablers and challenges for implementing I4.0 within PSCs (Section 5.1) and (2) the Gioia method enabled to develop the PSCRC model and identifies the dimensions of implementing I4.0 within PSCs to guide future research agendas.

4. Findings: conceptualisation of the PSCRC model

A thematic analysis was carried out to establish a thematic map aiming to provide information on the implementation of I4.0 within the PSC and its contribution to restructuring its resilient strategy. The Gioia Method was then applied to structure the data inductively. The identified data structure and results of the thematic analysis were consolidated to produce a model to develop an overarching framework to inform and guide future research (Figure 3). We present the data structure by emphasising second-order themes and overarching dimensions (see Appendix A). The supporting data and codes for the data structure in the Gioia method is presented in Appendix. The data structure was developed through iterative coding, where first-order concepts (e.g. personalisation, traceability) were extracted from the article findings and grouped into second-order

Table 2 Sources for thematic analysis identified through SLR

No.	References
1	Panda and Satapathy (2024)
2	Abdallah and Nizamuddin (2023)
3	Al-Khatib (2023a)
4	Al-Khatib (2023b)
5	Aloini *et al.* (2023)
6	Amoozad Mahdiraji *et al.* (2023)
7	Aslam *et al.* (2023)
8	Bag *et al.* (2023)
9	Bandhu *et al.* (2023)
10	Banik *et al.* (2023)
11	Bankuoru Egala *et al.* (2023)
12	Bapatla *et al.* (2023)
13	Bassiouni *et al.* (2023)
14	Benazzouz and Auhmani (2023)
15	Benevento *et al.* (2023)
16	Chen *et al.* (2023)
17	Debnath *et al.* (2023)
18	Emmanuel *et al.* (2023)
19	Erol *et al.* (2023)
20	Faheem and Dutta (2023)
21	Fasterholdt *et al.* (2023)
22	Gerrans *et al.* (2023)
23	Gomasta *et al.* (2023)
24	Goodarzian *et al.* (2023)
25	Havaeji *et al.* (2023)
26	Jraisat *et al.* (2023)
27	Khan *et al.* (2023a)
28	Kordestani *et al.* (2023)
29	Kumar Detwal *et al.* (2023)
30	Liu *et al.* (2023)
31	Ma *et al.* (2023)
32	Mariappan *et al.* (2023)
33	Mezquita *et al.* (2023)
34	Nanda *et al.* (2023)
35	Nguyen *et al.* (2023)
36	Ramos and Vigo (2023)
37	Sathiya *et al.* (2023)
38	Schneikart *et al.* (2023)
39	Seddigh *et al.* (2023a)
40	Seddigh *et al.* (2023b)
41	Sharma M. *et al.* (2023)
42	Sharma R. *et al.* (2023)
43	Spyrou *et al.* (2023)
44	Thakuriya *et al.* (2023)
45	Tsolakis *et al.* (2023)
46	Turki *et al.* (2023)
47	Wu *et al.* (2023)
48	Yadav *et al.* (2023)
49	Yang *et al.* (2023)
50	Yani and Aamer (2023)
51	Yazdinejad *et al.* (2023)
52	Zhang *et al.* (2023)
53	Ziaee *et al.* (2023)
54	Babu *et al.* (2022)
55	Chiacchio *et al.* (2022)
56	Humayun *et al.* (2022)
57	Joseph Jerome *et al.* (2022)
58	Mahdiraji *et al.* (2022)
59	Mariappan *et al.* (2022)
60	Nanda and Nanda (2022)
61	Nguyen *et al.* (2022)
62	Saha *et al.* (2022)
63	Sahoo *et al.* (2022)
64	Abideen and Mohamad (2021)
65	Alkhoori *et al.* (2021)
66	Erol *et al.* (2021)
67	Ghelichi *et al.* (2021)
68	He and Shi (2021)
69	Hosseini Bamakan *et al.* (2021)
70	Konovalenko and Ludwig (2021)
71	Konovalenko *et al.* (2021)
72	Koshta *et al.* (2021)
73	Li *et al.* (2021)
74	Liu *et al.* (2021)
75	Musamih *et al.* (2021)
76	Niu *et al.* (2021)
77	Pandey and Litoriya (2021)
78	Quintanilla García *et al.* (2021)
79	Sabbagh *et al.* (2021)
80	Singh and Chaddah (2021)
81	Uddin *et al.* (2021)
82	Zhan *et al.* (2021)
83	Zhu *et al.* (2021)
84	Abbas *et al.* (2020)
85	Alharthi *et al.* (2020)
86	Alles and Gray (2020)
87	Asrini *et al.* (2020)
88	Benita *et al.* (2020)
89	Chatterjee (2020)
90	Dwivedi *et al.* (2020)
91	Edussuriya *et al.* (2020)
92	Erokhin *et al.* (2020)
93	Hastig and Sodhi (2020)
94	Lamprou (2020)
95	Paul and Venkateswaran (2020)
96	Pence (2020)
97	Safkhani *et al.* (2020)
98	Saxena *et al.* (2020)
99	Singh *et al.* (2020)
100	Djunaedi (2019)
101	Hii *et al.* (2019)
102	Jamil *et al.* (2019)
103	Shafique *et al.* (2019a)
104	Shafique *et al.* (2019b)
105	Srivastava *et al.* (2019)
106	Álvarez López *et al.* (2018)
107	Ding (2018)
108	Festa *et al.* (2018)
109	Gonul Kochan *et al.* (2018)
110	Sylim *et al.* (2018)
111	Wu and Mao (2017)
112	Papert *et al.* (2016)
113	Wu *et al.* (2015)
114	Hendrik Haan *et al.* (2013)

themes based on conceptual similarity. For example, personalisation identified in Ding (2018) (reference #107), enhances customer satisfaction by enabling tailored treatments, contributing to reconfiguring capabilities. Traceability as noted in Nanda *et al.* (2023) (reference #34), supports coordination capabilities by improving supply chain transparency, contributing to sensing capabilities. To further clarify how the themes were inductively derived and how conflicting interpretations (e.g. whether AI enhances or complicates decision-making) were resolved, we provide detailed discussion in section 4.1, 4.2 and 4.3. For instance, we argue that I4.0 technologies, including AI, blockchain and data analytics can facilitate the development of a transparent PSC system. These technologies enhance data, information and knowledge sharing, thereby contributing to more robust decision-making. However, challenges related to security and safety must still be addressed. Mapping of the process by which I4.0 tools translated into resilience (e.g. how real-time visibility (IoT) → proactive risk sensing → faster disruption recovery) can be understood via the PSCRC framework and the rich description provided, ensuring a clear chain of evidence from data to model.

The aggregate dimensions presented in Figure 3 are related to the I4.0-enabled capabilities for developing sensing, seizing and reconfiguring capabilities, which will eventually lead to resilient PSCs. The thematic analysis suggests that the implementation of I4.0 technologies can contribute to developing coordination capabilities, which can be considered as sensing capabilities according to DCT. I4.0 technologies support the development of a transparent supply chain system where the availability of rich data sources and the power of data analytics enhances information/knowledge sharing and communication (Musamih *et al.*, 2021). The collection and analysis of insightful data builds the coordination capability that can simplify and foster PSC robustness, improve decision-making, and lead to a timely and efficient response to disruptions. Bag *et al.* (2023) studied absorptive capacity in healthcare organisations, which inherently rely on coordination, by implementing BDA and an AI collaborative platform.

Subsequently, data collection and analysis achieved through the coordination of capabilities enabled the development of important strategic procurement and process improvement capabilities. These ensure upstream and downstream PSC optimisation by improving the supplier selection and procurement process, while simultaneously enhancing accessibility to healthcare services. Nevertheless, implementing I4.0 technologies within the PSC leverages these seizing capabilities as they enhance information sharing, visibility, and stakeholder relationships, which are elements that contribute to the development of a resilient PSC.

Finally, the findings indicate that I4.0-based PSCs can offer not only accurate and faster diagnosis but also personalised treatments and, therefore, enable healthcare systems to effectively deal with patients' needs. I4.0 technologies support the PSC to achieve more sustainable production, which eliminates waste and cost, enhances forecasting, and increases flexibility that supports quicker responses to changes. Consequently, this environment supports PSCs to build reconfiguring capabilities, mainly supported by the dimensions of customer satisfaction and sustainable production.

The PSCRC model (Figure 1) conceptualises and presents the sensing, seizing, and reconfiguring capabilities. The contribution of I4.0 technologies to the PSC dynamic capability-building process that allows the development of resilient PSCs is discussed below.

4.1 Coordination (sensing) capability

Coordination is required across PSC networks to ease complex global supply chains and develop resilient PSCs. Traceability, visibility and transparency have emerged as crucial elements that contribute to sensing capabilities and enabling proactive risk management within a transparent supply chain environment. Joseph Jerome *et al.* (2022) and Erol *et al.* (2021) highlighted the need to adopt innovative approaches (e.g. Procurement 4.0) to build transparent PSCs. Table 3 presents the sub-themes related to this capability.

Figure 3 Data structure

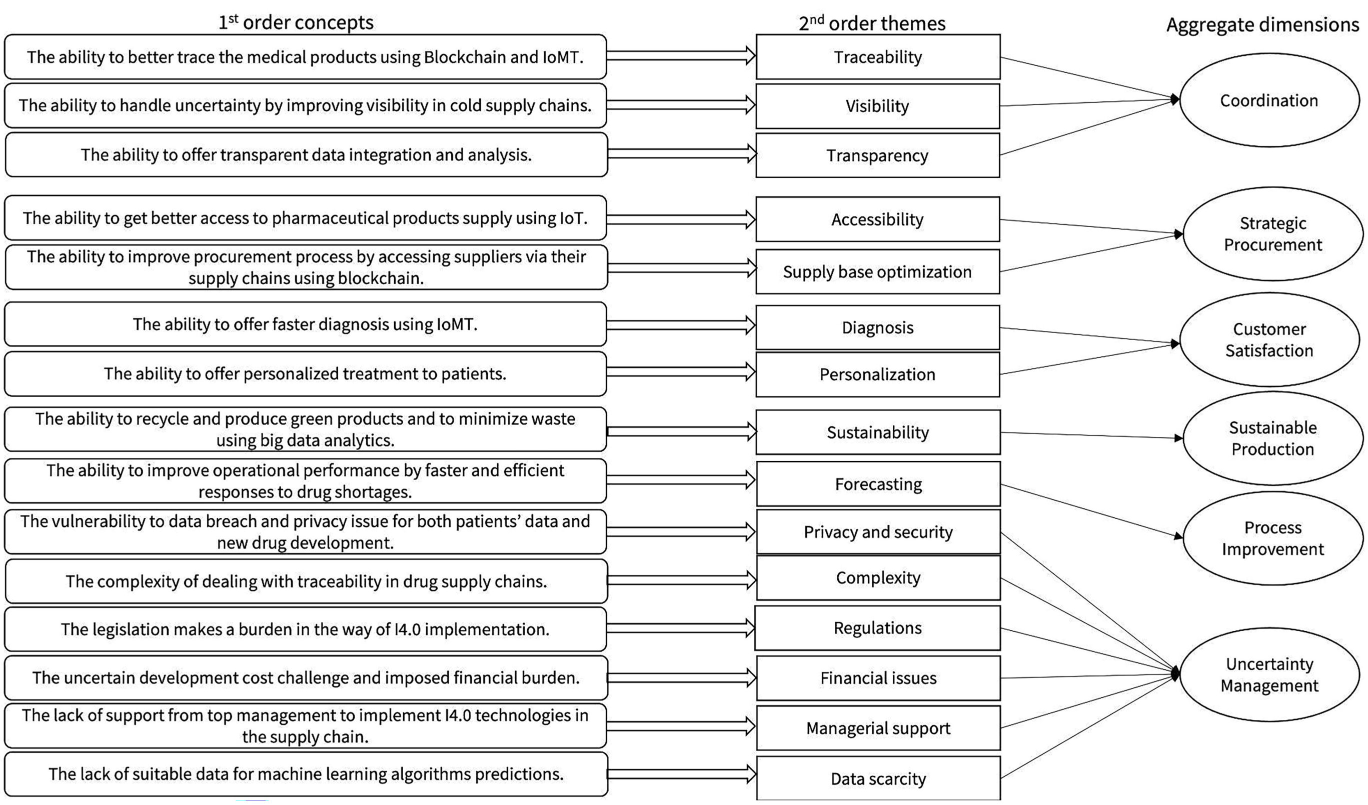


Table 3 Coordination capabilities

Sub-theme	Underlying codes	Industry 4.0 tools	Corpus references
Complexity	Aiding in complex decision-making; data gathering for medicinal products; improving interoperability issue; traceability; data transparency; integration; counterfeit medicines; supply chain visibility; resilience and flexibility	Procurement 4.0; AI; blockchain; IoMT; machine learning	1, 5, 6, 7, 8, 9, 15, 33, 37, 40, 43, 46, 48, 55, 56, 57, 59, 60, 62, 66, 68, 73, 74, 81, 84, 85, 86, 90, 92, 94, 95, 96, 97, 99, 100, 104, 105, 106, 107, 109, 112
Privacy, security and technical limitations	Vulnerability; transparency; security and privacy; storage capacity; traceability; complexity; interoperability issue; inventories optimisation challenge; visibility and coordination improvement challenge; digitalisation; collaboration; technological readiness; privacy-preserving issue; cyberattacks	Blockchain; AI; IoMT; data analytics; IoE;	9, 12, 29, 33, 40, 49, 51, 54, 56, 57, 58, 61, 62, 67, 68, 69, 71, 73, 74, 75, 76, 79, 81, 85, 89, 91, 93, 94, 96, 99, 101, 107, 109, 112, 114
Decision-making	Aiding in complex decision-making; improving stakeholder management; improving traceability; innovative procurement; creating data transparency; data analysis - integration	Procurement 4.0; ML-based solutions; BDA; blockchain; AI	5, 10, 24, 27, 29, 32, 35, 50, 53, 54, 55, 56, 57, 59, 60, 62, 64, 65, 67, 70, 73, 81, 87, 89, 90, 92, 93, 95, 99, 104, 105, 106, 107, 109, 112

4.1.1 Complexity

To simplify highly complex PSCs, researchers have suggested the adoption of blockchain technology to improve transparency and traceability by providing a secure and decentralised platform for tracking the movement of pharmaceutical products from manufacturers to patients (Alharthi *et al.*, 2020; Aloini *et al.*, 2023; Uddin *et al.*, 2021; Yazdinejad *et al.*, 2023). This technology can also improve coordination among healthcare stakeholders by providing a shared platform for data exchange and collaboration, which is one of the several challenges facing PSCs (Alharthi *et al.*, 2020; Alles and Gray, 2020). However, Benevento *et al.* (2023) empirically identified seven barriers to supply chain integration (SCI) using technologies in 30 case studies of the healthcare sector in Italy. Lack of motivation, unwillingness to change and lack of support from healthcare authorities were among the impediments, illustrating the low importance of financial resources in the studied cases.

4.1.2 Privacy, security, and technical limitations

Ding (2018) posits that I4.0 technologies in PSCs enhance coordination, efficiency and patient-centric flexibility. However, disparate IT systems among PSC stakeholders can hinder interoperability, compatibility and visibility, making PSCs vulnerable to data breaches and impeding traceability and transparency (Ali *et al.*, 2022; Bapatla *et al.*, 2023; Hendrik Haan *et al.*, 2013). Uddin *et al.* (2021) emphasised the lack of full interoperability in the current drug traceability solutions such as bar codes, blockchain systems and radio frequency identification (RFID) tags. Chatterjee (2020) and Singh *et al.* (2020) emphasised the need for data security and integrity in digital supply chains, particularly PSCs, owing to privacy concerns in advanced therapies. Regulatory compliance with patient security and privacy is a potential barrier to innovation in PSCs (Bandhu *et al.*, 2023; Paul and Venkateswaran, 2020). Abdallah and Nizamuddin (2023) proposed blockchain-based smart contracts to enhance stakeholder trust, transparency and data security.

4.1.3 Decision-making

Paul and Venkateswaran (2020) used machine learning (ML) algorithms to identify plausible crisis behaviours under deep uncertainty, aiding decision-making through improved supply chain policies (e.g. Kumar Detwal *et al.*, 2023). Chatterjee (2020) promoted Pharma 4.0 for performance enhancement through data-driven decision-making. Specifically, IoT generates integrated systems to gather data, and AI makes decisions based on these data, which leads to faster early diagnosis and offers personalised treatment (Goodarzian *et al.*, 2023). Nguyen *et al.* (2023) proposed AI for disruption-resilient demand forecasting, and Bassiouni *et al.* (2023) suggested deep learning (DL) for shipment risk mitigation. Cloud-based information sharing improves PSC visibility, and reduces costs and shortages (Gonul Kochan *et al.*, 2018). Erokhin *et al.* (2020), Aloini *et al.* (2023) and Srivastava *et al.* (2019) also focused on enhancing PSCs by analysing data to facilitate the decision-making process and advocate blockchain implementation for transparent, secure, and efficient PSC transactions (Abdallah and Nizamuddin, 2023; Chiacchio *et al.*, 2022; Havaeji *et al.*, 2023).

4.2 Strategic procurement and process improvement (seizing) capabilities

4.2.1 Operational performance

Erokhin *et al.* (2020) proposed distributed ledger technology as an innovative means of tracking pharmaceutical products throughout their life cycle, facilitating PSC management and addressing trust and confidentiality concerns. Chatterjee (2020) recommended the development of zero-trust networks to mitigate risks related to data integrity and network security. Big data predictive analytics (BDPA) and RFID technologies can also be implemented to improve supply chain performance, as stated by Shafique *et al.* (2019a, 2019b), enabling real-time product tracking and reducing misplacements. Nguyen *et al.* (2023) discussed the benefits of using linear programming (LP) to leverage news data to enhance performance and, more crucially, mitigate the risk of visibility loss during disruptions.

4.2.2 Resource constraint

I4.0 implementation necessitates the convergence of relevant stakeholders through standardised and integrated systems, an arduous endeavour for PSCs (Alharthi *et al.*, 2020), which contributes to immature infrastructure and scalability challenges (Paul and Venkateswaran, 2020). Integrated systems advance demand forecasting, which is particularly crucial for PSCs, as pandemics, such as COVID-19, can precipitate a surge in demand for certain emergency services, including pharmaceuticals (Zhu *et al.*, 2021). However, the low adoption of innovation within PSCs could stem from an inability or unwillingness to support long-term investments (Uddin *et al.*, 2021); lack of senior leadership support, attributed to PSC professionals' lack of knowledge about I4.0 implementation, and reluctance toward new technology training or change, often impedes progress (Papalexi *et al.*, 2022).

Table 4 presents the sub-themes related to strategic procurement and process improvement capabilities.

4.3 Sustainability and customer satisfaction (reconfiguring) capabilities

4.3.1 Sustainability

Alharthi *et al.* (2020) explored the sustainability and effectiveness of PSCs in Saudi Arabia, identifying product shortages, waste, lack of coordination among healthcare stakeholders, and inadequate medication demand information as key issues. Blockchain technology has been recommended as a solution, echoed by Liu *et al.* (2023) and Bankuoru Egala *et al.* (2023), who highlighted its potential to contribute to sustainability by improving transparency and accountability, and reducing waste and inefficiencies that harm patients and the environment. Indeed, Ding (2018) and Djunaedi (2019) found that Pharma Industry 4.0 can contribute to sustainable PSCs by improving flexibility, enhancing communication, reducing waste/pollution, and enabling autonomous decision-making. Al-Khatib (2023b) evaluated the impact of the industrial IoT on sustainability in Jordan's pharmaceutical manufacturing sector and identified a positive effect on sustainability performance and supply chain visibility.

In addition, blockchain facilitates the integration of reverse supply chain networks, thereby increasing the PSC sustainability performance (Jraisat *et al.*, 2023). Gerrans *et al.* (2023) proposed the adoption of a circular pharmaceutical supply chain (CPSC) model to facilitate reverse logistics and reduce unnecessary medicine waste, with significant quantities wasted globally, including an estimated £300m annually by the UK National Health Service (NHS) (Trueman *et al.*, 2010). Although Seddigh *et al.* (2023a, 2023b) revealed a strong relationship between business intelligence and sustainability, developing a sustainable PSC pathway is challenging because of obstacles such as lack of awareness and training on sustainable practices, high investment and time-consuming processes, poor leadership support, lack of regulations promoting sustainable development, and ineffective sustainable initiatives (Debnath *et al.*, 2023; Ding, 2018).

4.3.2 Customer satisfaction

The advancements in genomic research have facilitated the manufacturing of personalised pharmaceuticals. Patient-centred or personalised medicines are imperative as the elderly population with chronic diseases increases and reducing data density can enhance productivity and create added value by focusing on individualised medicine therapy rather than the "one-size-fits-all" approach (Bankuoru Egala *et al.*, 2023; Li *et al.*, 2021). Furthermore, failing to meet the two critical capabilities of PSCs, verifying authentic drugs and monitoring temperature conditions, can adversely affect customer satisfaction (Erokhin *et al.*, 2020; Faheem and Dutta, 2023). Although Trenfield *et al.* (2022) highlighted the significant benefits of virtual digital health technologies for patient care, challenges persist, ranging from data security to acceptance in the healthcare sector. Sharma *et al.* (2023) identified lack of customer awareness and satisfaction as impediments to sustainable implementations through the adoption of I4.0.

Table 5 presents the sub-themes related to sustainability and customer satisfaction capabilities.

5. Discussion

5.1 Theoretical implications and research avenues to build resilience in PSCs

The COVID-19 pandemic and the more recent "black swan" crisis have precipitated significant uncertainty across supply chains (Ali *et al.*, 2022), severely impacting globalised and complex PSCs (Papalexi *et al.*, 2020). This disruption has induced a pre-paradigm shift in PSC research. The present study aimed to explore the implementation of I4.0 within the PSC to foster resilience and develop capabilities to mitigate future disruptive events. Ali *et al.* (2022) underscored the significance of cultivating organisational capabilities to address external risks and enhance performance during crises. Joseph Jerome *et al.* (2022) examined how I4.0 technologies could be integrated into supplier evaluation and procurement processes, emphasising mutual growth, supplier capacity, willingness to implement I4.0, and the importance of collaboration for long-term procurement success.

The supply chain literature illustrates a range of strategies used by firms to establish a resilient supply network (Chopra *et al.*, 2021): (1) tailored sourcing or having multiple channels on the sourcing side; (2) omni-channel retailing or having multiple

Table 4 Strategic procurement and process improvement capabilities

Sub-theme	Underlying codes	Industry 4.0 tools	Corpus references
Operational performance	Time-sensitive medical supplies; early diagnosis; clinical and operational performance; process efficiency; traceability; demand forecasting; competitive advantage	IoMT; Pharma 4.0; blockchain; IoT	3, 10, 18, 24, 29, 35, 50, 53, 57, 62, 64, 66, 67, 72, 73, 78, 89, 90, 92, 99, 100, 103, 106, 107, 108, 109, 111
Resource constraint	Development cost; drug shortage; capabilities; high and unclear investments; technological readiness; inaccurate information	Blockchain; data analytics; Pharma 4.0	10, 12, 19, 49, 56, 57, 58, 59, 61, 62, 69, 73, 81, 83, 93, 95, 99, 101, 107, 109, 112

Table 5 Sustainability and customer satisfaction capabilities

Sub-theme	Underlying codes	Industry 4.0 tools	Corpus references
Sustainability	Green manufacturing; waste management; integrated reverse supply chain networks; circular pharmaceutical supply chain	Big data; blockchain; Pharma Industry 4.0; RFID; smart packaging system	4, 17, 21, 23, 39, 41, 63, 68, 81, 85, 95, 97, 98, 99, 100, 107
Customer satisfaction	Early diagnosis; personalised treatment	IoT, blockchain	11, 20, 41, 56, 73, 92, 99, 107

channels on the sales side; (3) investing in flexible capacity and its applicability through enhanced information sharing; (4) investing in caution, and (5) investing in risk mitigation inventory or reserve capacity. We discuss how these resilience-building strategies map onto our proposed model in the PSC through the lens of capabilities, and how I4.0 plays a role in each dimension of the theoretical framework.

In this context, Yaroson *et al.* (2021, 2023, 2024) decentralised blockchain-AI model management framework offers a novel mechanism for enhancing resilience through secure, distributed coordination and data governance. By integrating blockchain with federated AI learning, the framework enables real-time traceability, privacy-preserving data sharing and immutable audit trails, features that are particularly valuable in pharmaceutical environments where regulatory compliance and trust are paramount. The use of smart contracts and zero-knowledge proofs further supports automated decision-making and secure collaboration across stakeholders, aligning with the tailored sourcing and omni-channel strategies outlined above. Moreover, the framework's decentralised architecture facilitates scalable and transparent model training, which strengthens sensing and seizing capabilities by enabling predictive analytics and adaptive planning without compromising data confidentiality.

This integration of blockchain-AI technologies into I4.0 implementations represents a shift from centralised control to distributed intelligence, empowering PSCs to respond proactively to disruptions while maintaining operational integrity and patient safety. As such, Yaroson *et al.*'s framework complements existing resilience strategies and provides a technological foundation for dynamic capability development in the pharmaceutical sector.

5.1.1 Coordination capability

This capability is associated with all resilience strategies, taking advantage of I4.0. As emphasised in the literature, information sharing and coordination are pivotal for timely decision-making in a volatile, uncertain, complex, and ambiguous (VUCA) business environment. Cultivating coordination capabilities will enable the PSC to implement standardised confidential data collection practices across networks and develop the currently immature infrastructure to support suitable I4.0 implementations across the supply chain within the pharmaceutical sector, such as integrated IT systems throughout. This will foster transparent PSC systems capable of robust decision-making. Yaroson *et al.* extend this view with their proposed decentralised blockchain–AI model management framework that enables secure, traceable and privacy preserving coordination across distributed pharmaceutical nodes. We therefore present: Research Avenue (RA) 1: I4.0 technologies facilitate end-to-end coordination in pharmaceutical supply chains by enabling real-time traceability, systemwide visibility and secure data transparency – capabilities that reinforce the sensing capability and empower proactive risk mitigation, regulatory adherence and continuity of patient care.

5.1.2 Strategic procurement and process improvement capability

Strategic procurement capability can contribute to tailored sourcing and omni-channel retail strategies to make PSCs resilient using I4.0. Similarly, the process improvement capabilities enabled by I4.0 enhance operational performance, product traceability, trust and confidentiality in PSCs (Chatterjee, 2020; Erokhin *et al.*, 2020). Bag *et al.* (2023) explained that the omni-channel healthcare business has been defined in the literature (Cordon *et al.*, 2016) as an extension of conventional healthcare supply chains in which patients can connect with healthcare providers for consultations using virtual platforms such as telemedicine. Yaroson *et al.*'s framework compliments the strategies by enabling decentralised model training and secure stakeholder collaboration through smart contracts and zero knowledge proofs. This allows pharmaceutical firms to evaluate supplier performance and process improvements without compromising data privacy, while maintaining auditability and compliance. Consequently, we propose: RA 2: I4.0 technologies enhance strategic procurement efficiency in the pharmaceutical supply chain by enabling precision sourcing and integrated digital healthcare channels, thereby strengthening supply chain resilience, regulatory compliance, and patient-centric service delivery.

5.1.3 Sustainability and customer satisfaction capability

I4.0 technologies and innovations contribute to sustainability by improving flexibility, transparency, accountability, resource management, waste reduction and reverse supply chain integration (Alharthi *et al.*, 2020; Bankuoru Egala *et al.*, 2023; Ding, 2018; Jraisat *et al.*, 2023; Liu *et al.*, 2023; Paul and Venkateswaran, 2020; Uddin *et al.*, 2021). Yaroson *et al.* (2023, 2024) further demonstrate how blockchain–AI integration can support sustainable practices by enabling transparent life-cycle tracking, incentivising responsible data sharing and reducing energy consumption through decentralised processing. Thus, we suggest:

RA 3: I4.0 technologies enable pharmaceutical supply chains to implement sustainable production that contributes to configuring capability by developing flexibility and enabling them to proactively respond to external risks.

In addition, customer capabilities contribute to establishing an omni-channel retail strategy, leading to customer satisfaction through resilience. The restricted distribution channel previously seen during the COVID-19 period can be overcome using a wide variety of technologies to open new sales channels, thereby improving resilience within PSCs and contributing to customer satisfaction, particularly during disruptions. However, this approach introduces greater complexity and sophistication into the supply chain (Chen *et al.*, 2023). One proposition is to invest in the implementation of appropriate industry commons in PSCs (Chopra *et al.*, 2021). Enabling standardised, interoperable data exchange across platforms to reduce integration costs and enhance customer facing transparency is highlighted by Yaroson *et al.* (2021, 2023, 2024). Accordingly, we offer:

RA 4: The use of appropriate industry standards can lower the cost of using multiple channels via I4.0 technologies, leading to customer satisfaction capability in pharmaceutical supply chains.

5.2 Managerial implications

Uncertainty and disruptions within the PSC can lead to Coordination Challenges, according to the PSCRC model, including: Vulnerability and Complexity – I4.0 technologies, such as the IoT and advanced analytics, improve coordination by providing real-time data and insights, reducing vulnerability and complexity (Kandasamy *et al.*, 2025); Lack of Communication and Information/Data Sharing – Enhanced communication tools and integrated IT systems foster better information sharing, mitigating inefficiencies and medication shortages (Frederico *et al.*, 2023); Product Wastage and Inefficiency – Automation and predictive analytics support inventory management optimisation, reducing product wastage and inefficiency (Singh *et al.*, 2024). By developing Sensing Capability regarding Coordination, managers can develop strategies to manage this complexity effectively through I4.0 adoption, ensuring the seamless coordination and integration of diverse systems and data sources. This includes integrating clinical, regulatory and logistics data across global networks to support timely and compliant decision-making. Establishing robust governance frameworks and cross-functional teams can facilitate effective decision-making and streamline operations. Fostering a data-driven culture and investing in analytical capabilities are essential for effective decision-making. Yaroson *et al.* (2021, 2023, 2024) decentralised blockchain–AI model management framework further supports these efforts by enabling secure, traceable and privacy preserving coordination across distributed PSC notes, enhancing trust and transparency in real time decision-making.

In addition, there are Sourcing and Process Challenges regarding: High Number of Stakeholders and Long Lead Times – I4.0 facilitates better stakeholder coordination and reduces lead times through improved process visibility and automation (Kandasamy *et al.*, 2025); Unpredictable Demand Patterns – Advanced forecasting and demand planning tools enable more accurate predictions, addressing unpredictable demand patterns (Frederico *et al.*, 2023) and Immature Infrastructure and Low Trust Networks – Implementing blockchain and secure data-sharing platforms enhances trust and infrastructure maturity (Singh *et al.*, 2024). Developing the Strategic procurement and process improvement (seizing) capabilities, managers are able to evaluate resource constraints and develop comprehensive cost-benefit analyses to prioritise investments and ensure a sustainable return on investment. They can explore the adoption of advanced manufacturing techniques, such as additive manufacturing (3D printing) and continuous manufacturing processes, to enhance efficiency, reduce costs and improve product quality. In addition, leveraging predictive maintenance and real-time monitoring can optimise asset utilisation and minimise unplanned downtime. Yaroson *et al.*'s framework (2021, 2023, 2024) provides a decentralised infrastructure for managing AI model updates and data provenance, which is particularly valuable in multi- stakeholder pharmaceutical environments where trust, auditability and compliance are critical.

Furthermore, the Sustainability Challenges concerning Lack of Awareness and Training Regarding Sustainable Practices can be addressed by I4.0 technologies, which support training and awareness programs through digital platforms, promoting sustainable practices (Kandasamy *et al.*, 2025); Lack of Flexibility and Poor Integration of Reverse Supply Chain Networks – Enhanced flexibility and integration of reverse logistics are achieved through IoT and advanced analytics (Frederico *et al.*, 2023), and High Investment – While initial investments are high, the long-term benefits of I4.0, such as cost savings and efficiency gains, justify the expenditure (Singh *et al.*, 2024).

By developing the Sustainability and Customer Satisfaction (Reconfiguring) Capabilities, managers explore opportunities to reduce waste, optimise energy consumption and minimise environmental impacts through intelligent resource management and circular economic principles. In addition, leveraging digital twins and simulation tools can aid in sustainable product design and process optimisation. I4.0 supports sustainable supply chain practices by improving flexibility, reducing waste, and enhancing forecasting (Kandasamy *et al.*, 2025). In the pharmaceutical context, this includes optimising cold chain logistics, reducing expired product returns, and improving packaging sustainability. They can also focus on leveraging advanced analytics and real-time data to anticipate customer needs, personalise offerings and provide transparent and timely information throughout a product's lifecycle. Yaroson *et al.*'s model contributes to sustainability by enabling decentralised, transparent life-cycle tracking and incentivising responsible data sharing, supporting circular economy principles and long-term value creation in PSCs.

6. Conclusion

The uncertainty generated by disruptions underscores the importance of reimagining and building resilient PSCs by leveraging the capabilities of I4.0 technologies, presented by the PSCRC model (Figure 1). Consequently, this study advances the extant literature by investigating how the vast opportunities and capabilities afforded by I4.0 can be implemented to construct robust PSCs capable of reducing vulnerability to disruptions. The successful implementation of I4.0 in PSCs necessitates a holistic approach that addresses various management implications. By proactively managing complexity, ensuring data privacy and security, fostering data-driven decision-making, optimising operational performance, addressing resource constraints, promoting sustainability and enhancing customer satisfaction, organisations can effectively navigate the challenges and capitalise on the opportunities presented in I4.0. We believe in the importance and timeliness of our research by emphasising the need for developing innovative solutions to strengthen PSCs and highlighting the paucity of research on I4.0 technologies' adoption in this context (Bapatla *et al.*, 2023; Yaroson *et al.*, 2023; Raj *et al.*, 2022).

The proposed PSCRC model elucidated the critical capabilities required to bolster the resilience of PSCs in the face of unforeseen events and disturbances, which contributes to the call for digital-sustainable business models identified by Palmié *et al.* (2024). By proposing the synergistic interplay between I4.0 technologies and DCT, the PSCRC model offers a comprehensive framework to augment the adaptability, responsiveness and robustness of PSCs, thereby mitigating the adverse impacts of supply chain disruptions on pharmaceutical operations and ensuring a continuous and uninterrupted flow of essential medical supplies. This contributes to the lack of the operationalisation of the construct of capabilities reported by Bruyaka *et al.* (2024) and Yaroson *et al.* (2023). This research has a few limitations such as taking a holistic approach for I4.0 technologies in PSCs and using secondary data relying on limited published scholarly studies which can be overcome by adopting specific I4.0 technologies and empirically studying their implementation in PSCs. The limitations call for future research as are reflected on four overarching research directions based on a viewpoint that guides research agendas, which we believe will inspire scholars to contribute to this topical research area and help practitioners better manage future disruptions. The set of future avenues developed from these insights provide a basis for further empirical studies in this emerging research domain.

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Appendix

Table A1 Representative supporting data and codes for the data structure in the Gioia method

Second-order themes	Representative first-order data	Representative codes	Corpus references
Traceability	The ability to better trace the medical products using blockchain and IoMT	Traceability; collaboration; governance of traceability efforts; traceability in drug supply chains; implementing traceability; improving traceability	9, 34, 46, 48, 54, 57, 66, 74, 86, 93
Visibility	The ability to handle uncertainty by improving visibility in cold supply chains	Visibility; supply chain visibility; coordination	3, 4, 99, 107, 109, 112
Transparency	The ability to offer transparent data integration and analysis	Transparency; data transparency; improving transparency	1, 5, 6, 7, 55, 56, 59, 60, 81, 92, 104, 105, 106, 107, 109, 112
Accessibility	The ability to get better access to vaccines and medicines supply using IoT	Vaccine offering	3, 4, 16, 24, 46, 48, 67, 68, 89, 97, 104, 112, 114
Supply base optimisation	The ability to improve procurement processes by accessing suppliers via their supply chains using blockchain	Procurement; Innovative procurement; Procurement 4.0	57, 73, 74, 90, 92
Diagnosis	The ability to offer faster diagnosis using IoMT	Early diagnosis	7, 73
Personalisation	The ability to offer personalised treatment to patients	Personalised treatment	11, 20, 41, 56, 99, 107
Sustainability	The ability to recycle and produce green products and to minimise waste using big data analytics	Sustainability; green manufacturing; improved sustainability	4, 17, 21, 23, 39, 41, 63, 68, 81, 85, 95, 97, 98, 99, 100, 107
Forecasting	The ability to improve operational performance by faster and efficient responses to drug shortages	Demand forecasting	4, 29, 35, 50, 77, 83
Privacy and security	The vulnerability to data breach and privacy issue for both patients' data and new drug development	Privacy; privacy-preserving issue; protecting privacy	9, 12, 29, 33, 40, 49, 51, 54, 56, 57, 58, 61, 62, 67, 68, 69, 71, 73, 74, 75, 76, 79, 81, 85, 89, 91, 93, 94, 96, 99, 101, 107, 109, 112, 114
Complexity	The complexity of dealing with traceability in drug supply chains	Complexity; handling complexity	1, 5, 6, 7, 8, 9, 15, 33, 37, 40, 43, 46, 48, 55, 56, 57, 59, 60, 62, 66, 68, 73, 74, 81, 84, 85, 86, 90, 92, 94, 95, 96, 97, 99, 100, 104, 105, 106, 107, 109, 112
Regulations	The legislation creates a burden for I4.0 implementation	Legislation issues	81, 92, 99, 107, 109
Financial issues	The uncertain development cost challenge and imposed financial burden	Financial issues; development cost; financial cost	62, 85, 86, 95
Managerial support	The lack of support from top management to implement I4.0 technologies in the supply chain	Top management support; collaboration; management support	32, 57, 61
Data scarcity	The lack of suitable data for machine learning algorithms predictions	Limited data access	18, 29, 32, 49, 50, 58

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