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The Impact of COVID-19 on Industry 4.0 Adoption: An Emerging Economy Perspective

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ABSTRACT

The disruptions that COVID-19 precipitated on the world economy made it hard for companies to maintain their operations and achieve sustainable supply chain management. To address these challenges, companies had to leverage a new set of resources. This study, employing a desk-based qualitative research approach, investigated how COVID-19 drove companies to adopt Industry 4.0 technologies in their supply chain management and how these technologies, including artificial intelligence and the Internet of Things, in turn, drove supply chain resilience among firms in emerging countries. Through a comprehensive review of scholarly articles and publications from various organizations, the study employed the triangulation method to ensure the validity and reliability of the findings. The data collection adhered to specific criteria, including relevance, credibility, and publication date post-2020, aligning with the period when the COVID-19 pandemic began. Through a content analysis of these diverse data sources, mainly capturing the sentiments of industry players, three main findings emerged. First, the adoption of Industry 4.0 technologies has had a significant impact on the resilience of supply chain management in emerging economies during the COVID-19 pandemic. Second, the characteristics of emerging economies, such as limited infrastructure and a lack of technological proficiency, significantly influence the effectiveness of Industry 4.0 in enhancing supply chain resilience. Third, the long-term implications of Industry 4.0 adoption on supply chain resilience in emerging economies post-COVID-19 are multifaceted, encompassing both positive and negative effects. Based on these findings, the study recommends that companies in emerging economies invest in infrastructure, training and development, seek government support, address data privacy and security concerns, and plan for the long-term implications of Industry 4.0 adoption. This research, anchored in a robust dataset, provides valuable insights into the role of Industry 4.0 technologies in enhancing supply chain resilience in emerging economies during the COVID-19 pandemic and the challenges that companies in these economies may face in implementing these technologies.

Keywords: *automation, COVID-19, crisis, emerging economies, industry 4.0 technologies, inventory management, resource optimisation, SSCM*

1. INTRODUCTION

When COVID-19 became a global pandemic starting in 2020, it upended many structures of the global supply chain through mandated lockdowns, stay-home orders, and restricted transportation. Businesses had to drastically adjust their operations to stay afloat. Companies faced many challenges in adjusting to this new reality, but simultaneously, there emerged opportunities that largely leveraged emerging technology. Industry 4.0 became a crucial aspect of sustainable supply chain management (SSCM) as companies in many industries had to replace or complement human elements of their workforce. At the same time, the pandemic came at a time when SSCM, a practice that involves responsible use of resources in order to reduce the adverse impact of the production, purchase, and supply of goods on the environment, society, and economy (Panigrahi *et al.*, 2019), had become a major priority for the global community. Technology is a key tool in the implementation of SSCM (Panigrahi *et al.*, 2019). By adopting Industry 4.0 as a response to COVID-19 disruption, companies were therefore implementing a major pillar of SSCM (Agrawal *et al.*, 2020).

One key research gap is the lack of data and information on the environmental impact of Industry 4.0 technologies in the supply chain. While there is a growing awareness of the potential benefits of these technologies, there is still limited data on their actual impact. This makes it difficult to accurately assess the sustainability of supply chain management practices that incorporate Industry 4.0 technologies. Accordingly, this study seeks to understand how Industry 4.0, deployed as a response to disruptions caused by COVID-19, affected supply chain resilience amid disruptions caused by the pandemic.

As the pandemic rapidly spread across the globe, the first publicly acknowledged case of COVID-19 was reported in December 2019 in Wuhan, China. Within three months, cases had been reported on all continents across the globe, and policymakers rushed to implement containment measures that significantly changed the way production and distribution of goods are done (Narayanamurthy and Tortorella, 2021). Globally, the COVID-19 pandemic had significant ramifications on the three main stages of the supply chain: sourcing, manufacturing, and delivery (Bag *et al.*, 2021). Among the mitigations that governments put in place to contain the disease are social distancing and lockdowns. This meant that many facilities on different levels of the supply chain had to operate with limited resources, thus constraining capacity. In effect, argue Belhadi *et al.* (2021), COVID-19 was one of the biggest tests of the resilience of the global supply chain of manufactured goods. The result was a significant reduction in production capacity. For example, in Asia, 45% of manufacturers experienced shortages in requisite raw materials and 30% reported worker shortages (Agrawal *et al.*, 2020).

In response to these challenges, the fourth industrial revolution, or Industry 4.0, is one of the defining phenomena of the 21st-century tech space. Agrawal *et al.* (2020) conceptualize Industry 4.0 as a phenomenon characterized by increased connectivity, artificial intelligence and machine learning, automation through advanced robotics, and advanced engineering. Industry 4.0 is not a new phenomenon, with many experts agreeing that it has been raging since the start of the 21st century. With unprecedented capabilities and ubiquitous presence, the tools of Industry 4.0 presented a natural substitute to the labor resources compromised by COVID-19 (Njomane and Telukdarie, 2022).

When trying to fill the void left by workers who could not be at their conventional workspaces, those companies that turned to such technologies realized that there were opportunities that were previously unexploited (Hussain *et al.*, 2021). Reza *et al.* (2022) argue that the use of big data analytics gave supply chain managers unprecedented insight into customer demand and floor efficiency. On the production floor, the use of advanced robotics and machine learning brought about new levels of efficiency, increasing production and revenue for many companies in the manufacturing sector (Dongfang *et al.*, 2022). In the developing world, companies that did adopt Industry 4.0 technologies as a response to COVID-19 containment measures were essentially making a leap from very low-tech production (Nayal *et al.*, 2021). That did not stop them from gaining benefits from the adoption of Industry 4.0. In India, where Industry 4.0 was and is still at infancy, a study by Sharma *et al.* (2022) found that the use of Industry 4.0 resulted in positive effects on supply chain measures across the board.

This leads us to consider several research questions that are critical in exploring the extent and impact of Industry 4.0's integration into supply chain management during the COVID-19 pandemic:

1. How has the adoption of Industry 4.0 technologies impacted the resilience of supply chain management in emerging economies during the COVID-19 pandemic?
2. How do the characteristics of emerging economies influence the effectiveness of Industry 4.0 in enhancing supply chain resilience during the COVID-19 pandemic?
3. What are the long-term implications of Industry 4.0 adoption on supply chain resilience in emerging economies post-COVID-19?

These questions are explored through a thematic analysis of both academic and grey literature, focusing on extracting insights through an inductive process to apply broader theoretical findings to specific contexts. The paper is organized into the following main sections: Literature Review, Research Design and Methodology, Findings, and Conclusions and Recommendations. Briefly, the Literature Review assesses existing research and integrates it with foundational theories of supply chain management. The Research Design and Methodology section details the approaches for data collection and analysis used in our study. Findings are discussed comprehensively, linking them back to the research questions and theoretical frameworks. The paper concludes with practical recommendations for leveraging Industry 4.0 to enhance supply chain resilience in the challenging business environments of emerging economies.

2. LITERATURE REVIEW

2.1 Theoretical Framework

The resource-based view (RBV) developed by Barney (1991) is a theoretical framework that can be used to understand the use of Industry 4.0 at the firm level in ensuring supply chain management resilience during COVID-19 in emerging economies. According to RBV, a company's resources and capabilities are key determinants of its competitive advantage and long-term success (Barney, 1991; Kraaijenbrink *et al.*, 2010). In the context of SSCM, resources and capabilities related to Industry 4.0 technologies, such as artificial intelligence (AI) and the Internet of Things (IoT), can enhance resilience and mitigate the impact of disruptions like those caused by COVID-19 (Salam, 2019). RBV is particularly relevant to the current analysis as it focuses on the efficient utilization of scarce resources at the firm level, aligning with the characteristic of resource scarcity in emerging economies. Moreover, RBV offers a strategic perspective for companies in these economies, guiding the identification, development, and leveraging of resources that contribute to sustainability, economic growth, and competitiveness. Thus, RBV helps in understanding current challenges and provides a forward-looking approach for building resilience for sustainable success in the complex landscape of emerging economies.

A key aspect of RBV is the uniqueness of a company's resources and capabilities. Resources that are rare, valuable, and inimitable provide a competitive advantage and increase a company's resilience (Koh *et al.*, 2019). The relationship between RBV and SSCM is evident in how sustainable practices can be considered unique resources that contribute to competitive advantage. Shibin *et al.* (2020) view SSCM practices as a subset of resource-based approaches leading to the optimization of scarce resources. Environmental friendliness and circular economy initiatives provide a competitive edge while also appealing to customers who value sustainability (Shibin *et al.*, 2020). Therefore, SSCM can be seen as a means for companies to build and leverage sustainable resources and capabilities for competitive advantage. Koh *et al.* (2019) argue that Industry 4.0 technologies, especially those that are innovative, can be considered rare and valuable resources. Adopting these technologies can provide emerging economies with a competitive advantage and enhance supply chain resilience.

Another important aspect of RBV is the concept of dynamic capabilities, which refers to a company's ability to adapt and respond to environmental changes. In the context of supply chain management, Industry 4.0 technologies enhance dynamic capabilities by providing real-time data and enabling informed decision-making (Salam, 2019; Lopes de Sousa Jabbour *et al.*, 2022). This helps firms in emerging economies quickly identify and respond to disruptions like those caused by COVID-19, thus increasing their resilience. However, the effectiveness of Industry 4.0 in enhancing supply chain resilience in emerging economies may be influenced by contextual factors such as

technological infrastructure, availability of skilled labor, and investment levels in Industry 4.0 technologies (Lopes de Sousa Jabbour *et al.*, 2022).

2.2 The Essence of SSCM

In order to adequately appraise and understand the literature, there is a need to delineate the meaning and scope of SSCM and its attendant concepts. Seuring and Muller (2008) define SSCM as "the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements" (pp. 1700). The gatekeepers of the underlying processes are guided by conventions such as the Paris Agreement and local laws governing the implementation of a circular economy. Attendant changes include cutting greenhouse gas emissions, reducing freshwater usage, and embracing recycling to address challenges such as climate change, water inequality, and plastic waste (Bové and Swartz, 2016). In the face of rising global population and demand for resources, the push for SSCM serves as an opportunity for both communities and the companies implementing its attendant features (Bag *et al*., 2021).

The relationship between supply chain sustainability and supply chain resilience, central to this analysis, is crucial. Supply chain resilience entails a firm's ability to withstand external disruptions through predictive and adaptive capabilities that allow it to anticipate and respond to emergent challenges (Carissimi *et al.*, 2023). Carissimi *et al.* (2023) view sustainability and resilience as subsets of the supply chain, making it impossible to wholly separate the two concepts. Within the RBV theoretical setup, resilience would be seen as the aspect that qualifies SSCM as a component of RBV.

When assessing SSCM's relevance and usefulness in firms in emerging economies, the idea of scarce resources and their optimized utilization is highly relevant. As mentioned in the second research question, emerging economies are characterized by scarce infrastructure, technological expertise, and capital. Literature connecting SSCM's value with resource utilization is abundant. Sharma and Iyer (2012) found a close connection between sustainable supply chains through green production in China and India and the reality of scarce resource utilization inherent in emerging countries. This connection benefited firms during COVID-19 pandemic. Saeed and Kersten (2019) argue that sustainability practices are more viable in emerging countries because they are implemented out of necessity, whereas in developed countries, firms place a premium on sustainably availed goods and services. For Nandi *et al.* (2021), the scarcity issue precipitated by COVID-19 required three activities to implement SSCM: localization, digitization, and agility. This ties back to the concept of simplification as envisioned in RBV.

2.3 The COVID-19 Link to Supply Chains

The effect of COVID-19 on supply chains has been a prominent focus of scientific inquiry over the past two years. However, much of the research has taken a qualitative view, with many efforts in the economic field largely skirting hard numbers and statistics on different aspects of the global supply chain. The connection between COVID-19 and global supply chains lies in the pandemic's ability to disrupt labor resources and the movement of goods and people. The relevance of the pandemic in SSCM is further enhanced by the way it induced changes congruent with those aspired to by policymakers and industry players who sought to induce sustainability in all aspects of production (Seuring *et al.*, 2022). Responding to restrictions brought about by COVID-19 largely required prudent utilization of resources, innovative solutions to a constrained operational environment, and the recycling of various raw materials and products, which are the same principles on which SSCM is pegged (Bag *et al.*, 2021). Specifically, from the perspective of emerging economies, the pandemic disrupted a supply chain already plagued by inefficiencies, including poorly developed infrastructure and disjointed financial systems.

It is from this perspective that much of the scientific literature on the economic effects of the pandemic in the emerging world is written. In the developing world, the RBV concept most relevant to supply chain management is capabilities. According to Barney (1991), capabilities are created from resources that an entity possesses, with companies having the most dynamic capabilities being able to adjust quickly to changes in their environment. Because emerging countries have a more varied supply chain that includes a large informal sector, existing channels remained largely unaffected as COVID-19 disrupted formal channels. Njomane and Telukdarie (2022) found that food supply chains in South Africa remained resilient even in the face of border closures and the shutting down of production plants. The food shortages observed early in the pandemic were connected to panic buying by residents fearful of further disruption of the food industry. Seuring *et al.* (2022) confirmed the existence of large disparities between different geographical locations, with countries in South Asia, South America, and Africa having a unique set of challenges to their SCM compared to developed parts of Europe and North America. The RBV's contextualization of resources as a varied collection of assets that enable economic activities shows relevance in this effort because it considers challenges to mobilizing resources such as labor, equipment, employee training, and organizational interrelationships. Even though the literature assessed in this section does not explicitly jump off from the tenets of this theory, the ideations put forward by the researchers are highly aligned with the concepts of RBV.

2.4 The Use of Industry 4.0 in Supply Chain Management

Academic research has recognized Industry 4.0 aspects as being at the forefront of streamlining supply chain channels that were upended by COVID-19. Much of the research has centered on its application in developed countries and the inquiry on emerging countries has been relatively scant. One of the most direct forays into the use of Industry 4.0 to overcome COVID-19 -related challenges was done by Kumar *et al.* (2020), using a desk-based review of related keywords on scholarly databases. In that study, Kumar *et al.* (2020) identified 12 operational

challenges that were affecting the retail sector and which industry 4.0 was critical in handling. Among the challenges identified include a lack of flexibility in the supply chain implementation, poor cooperation and coordination among players in respective supply chains, communication issues between different entities in the supply chain ecosystem, and lack of access occasioned by transport problems. The researchers prop Industry 4.0 as harboring solutions for each of those problems by creating a single terminal through which the different functions of production and distribution are coordinated. This analysis fits well into the ideations of the resource-based perspective related to the concept of dynamic capabilities.

The term Industry 4.0 denotes a continuation of adaptations that started with the industrial revolution of the 19th century. As a set of highly synergetic physical and non-tangible resources, Industry 4.0 contains a mix of the qualities of the resource homogeneity and mobility described by Barney (1991). Industry 4.0 implementation relies on software, cloud technology as well as a plethora of physical technology assets such as servers and PCs. The ability to flexibly deploy the technologies of Industry 4.0 can be attributed to the competitive advantage that RBV emphasizes as an end for companies implementing it. Klingenberg (2017) emphasizes that Industry 4.0 is a revolution in its own right characterized by technical advancement, economic transformation and demographic changes. The first industrial revolution was marked by a proliferation of mechanized production and a rapidly growing youthful population. In the current era, information technology, massive economic gains and a growing senior population characterize the environment for Industry 4.0. The demographic changes in economically advanced regions are characterized by a declining working age population while in developing countries that section of the population is growing rapidly (Klingenberg *et al.*, 2022). In general, many countries in the emerging world were stuck in what Klingenberg *et al.*'s characterization is effectively industry 3.0 or earlier, with adoption of computer technology and automation being barely implemented. However, big data and AI, the differentiating aspects of industry 4.0 were largely unimplemented in these economies as compared to the scenario in advanced countries (Kumar *et al.*, 2020). Nayal *et al.* (2022) conducted a study in India, seeking to understand the factors that affect the adoption of AI in supply chain risk mitigation. Their study found that there are significant technological, environmental and infrastructural factors that determine the rate of adoption of AI. Specifically in emerging economies, these challenges are highly relevant, which is in contrast to the well-established systems in developed economies. Ogah and Onuoha (2022) frame the digital supply chain management evolution in Africa as one abounding with opportunities but ultimately plagued by barriers associated with a poorly developed technology ecosystem. Again, this view can be located at the heart of the resource-based perspective as an endeavor in the allocation and optimization of what amounts to scarce resources.

The use of Industry 4.0 tools, mainly big data and artificial intelligence, in the supply chain has been slowly spreading since the early 2010s. Zamani *et al.* (2023) caution that the move from insights to decision making, one of the major strengths of AI, still needs human-led intervention, and thus is still open to blind spots and poor interpretation. As such, there is a need for more research into the connection between human behavioral tendencies and emotional subjectivities, and their impacts in supply chain management. Modgil *et al.* (2021) conducted a research study with the aim of demystifying the role of AI in creating visibility, risk management capability and sourcing and distribution of products, finding that AI can enhance supply chain resilience by increasing transparency, enabling last-mile delivery, creating personalized solutions and tempering the effects of disruption. These suggestions bode well with the disruptive and uncertain environment brought about by the COVID-19 pandemic in the global economic supply chain. Equally, Ali (2022) recommended the extensive use of industry 4.0 elements along with blockchain and other complementary techniques in order to digitize the supply chain. Ali asserts that the digitization of the supply chain creates an optimal inventory maintenance which is a benefit that many companies will continue to exploit long after the pandemic has passed.

Generally, literature points to the onset of COVID-19 as being an incidental circumstance for pushing Industry 4.0 into the realm of supply chain management. While there has been widespread research into the implementation of Industry 4.0 in advanced economies, there are research gaps in its implementation in emerging economies, specifically with relation to responding to COVID-19. Some areas that need more concerted investigation include:

- Lack of understanding of the most effective ways to adopt and implement Industry 4.0 technologies in emerging economies, particularly in the context of the unique challenges and constraints faced by these countries.
- Limited research on the potential social and economic impacts of Industry 4.0 adoption in emerging economies, including the potential impact on employment and the need for workers to acquire new skills.
- Limited data and case studies on the effectiveness of Industry 4.0 technologies in addressing supply chain disruptions caused by COVID-19 and other crises.

As such, knowledge and insights on industry 4.0 as an intervention mechanism in developing countries is rather dispersed and there needs to be concerted effort to harmonize new and existing literature into a unitary framework that extrapolates from the lessons gained in enhancing the resilience of supply chains in different industries during the pandemic. Viewing the literature assessed under this literature review from a resource-based perspective reveals the synergetic linkages that exist between different resources and companies as envisaged by proponents of the theory. The RBV theory is particularly fitting for this analysis because the effects of COVID-19 on the global supply chain involved immobilizing various key resources needed to keep it running.

3. RESEARCH DESIGN AND METHODOLOGY

The current research takes an inductive approach. An inductive approach is well-suited for this study because it allows for the exploration of emerging patterns, themes, and insights from the collected data without preconceived hypotheses. Given the dynamic and multifaceted nature of the interactions between COVID-19, supply chains, and sustainability, an inductive approach enables a comprehensive understanding by letting the themes and patterns naturally emerge from the literature and empirical evidence. This approach is particularly effective when dealing with complex, context-dependent phenomena, providing a nuanced and contextually rich perspective that aligns with the exploratory nature of the study.

3.1 Data Collection

The current study used a review of grey and academic literature to gather data and sentiments on the use of Industry 4.0 to enable resilient and SSCM as a response to the economic disruption caused by COVID-19. A desk-based qualitative research approach takes the form of a study using secondary data contained in research articles, reports and other published material either found online or in physical repositories such as public libraries (Johnston, 2014). This approach is advantageous because it is convenient and cost-effective while providing in-depth and verified information on experiences and perspectives of the people involved in the phenomenon being researched (Bassot, 2022). The current research effort used sources such as journal articles and publications by various organizations. The first step involved using Google Scholar and other academic databases to find relevant documents available online and then listing them systematically according to their core subject.

3.1.1 Quality Control

In order to increase the rigor of the data collection and analysis exercise, the current research used the triangulation method. Under this approach it is recommended to collect a diverse range of data sources to triangulate the findings and increase the validity and reliability of the study. This could include a variety of types of sources, such as research articles, reports, conference proceedings, and other published materials (Bassot, 2022). For this research, the main type of source used was journal articles, combined with several industrial and government reports. Additionally, it is important to ensure that the individual materials that are used meet a certain threshold of quality and trustworthiness. The threshold for including any source that showed up in the search results was based on these three criteria which are part of the CRAAP test developed by Blakeslee (2004):

1. Date: to ensure that it adequately captures contextual data, sources had to have been researched and published in 2020 or later, during which period the COVID-19 pandemic had already been declared and its effects had begun being felt.
2. Credibility: there is no shortage of sources talking about Industry 4.0 but a vast majority of these are on blogs and websites with low levels of peer oversight. As such all the materials analyzed are either high quality reports by reputable organizations, and peer-reviewed journal articles.
3. Relevance: when vetting available sources, it was crucial to ensure that the information contained therein was relevant to the central topics of COVID-19, sustainability, and industry 4.0. They had to display an adequate level of interlinkage between these topics to stay close to the central purpose of the study. This is a highly subjective criterion but using close inspection of keywords as utilized and discussed within the materials should ensure a successful vetting.
4. Validity: the validity of a research study or article reflects how generalizable the findings contained therein are to the population outside the study. It should be reflective of reality both within and outside the sample to be considered valid. This criterion was largely met by a vast majority of the papers, and those that did not meet this criterion had already been abrogated due to other criteria.
5. Reliability: this criterion relates to the reproducibility of results in a research study by using the same instruments and methodology used in the study. It is an indicator that the results capture an accurate snapshot of the truth at any given time.

As a result of the vetting using the five criteria in the CRAAP test, a total of 32 articles were found to fit the required threshold for use in the content analysis phase.

3.1.2 Content Analysis

The software WordStat was used to collectively analyze the 32 articles that were chosen for their relevance to a specific research topic. WordStat is a data analysis and text mining software developed by Provalis Research. It is particularly useful for content analysis of qualitative data, allowing for in-depth exploration of textual information and identification of meaningful patterns. The first step in the process involves downloading all the articles from their respective sources. After downloading the articles, they were loaded onto WordStat for comprehensive analysis. Based on an automated analysis of the text, the software identified key words and phrases, patterns, and relevant topics within the content. The keyword extraction tool in WordStat facilitated the extraction of essential keywords and phrases from the articles. This automated process helped reveal the prevalent topics and trends across the dataset. The resulting keyword distribution highlighted the frequency and significance of specific terms within the collective body of text. Through WordStat's analytical capabilities, valuable insights into the overarching themes and content structure present in the 32 articles were gained. This content analysis approach allowed for a systematic examination of the textual data, providing a basis for informing research conclusions. The findings derived from WordStat's analysis contribute to a deeper understanding of the qualitative aspects present in the selected articles and serve as a foundation for further exploration and interpretation.

When the software analyzed the documents in their entirety for keywords, patterns and topics, the following emerged as the most dominant phrases and were used as the codes for the content analysis. In order to ensure relevance of the included data, only phrases with more 30 or more occurrences in the entire dataset of 34 articles were included.

Table 1 Key phrases identified by WordStat from the dataset (F>30)

PHRASE	FREQUENCY	NO. CASES	% CASES	LENGTH
Supply chain	3181	31	100.00%	2
Supply chains	773	31	100.00%	2
Supply chain management	472	27	87.10%	3
Covid pandemic	408	29	93.55%	2
Industry technologies	384	20	64.52%	2
Big data	331	28	90.32%	2
Supply chain resilience	258	23	74.19%	3
Food supply chain	242	13	41.94%	3
Circular economy	215	20	64.52%	2
Real time	185	27	87.10%	2
Decision making	174	23	74.19%	2
Internet of things	149	26	83.87%	3
Post covid	148	20	64.52%	2
Sustainable supply chain	148	19	61.29%	3
Additive manufacturing	142	15	48.39%	2
Covid outbreak	128	22	70.97%	2
Big data analytics	118	19	61.29%	3
Risk management	109	15	48.39%	2
Long term	108	24	77.42%	2
Digital technologies	101	19	61.29%	2
Blockchain technology	98	18	58.06%	2
Supply chain mapping	98	3	9.68%	3
Sustainable food supply chain	97	3	9.68%	4
Operations management	94	22	70.97%	2
Sustainable development	94	18	58.06%	2
Project management	90	5	16.13%	2
Global supply	86	23	74.19%	2
Cloud computing	82	18	58.06%	2
Supply chain disruptions	82	15	48.39%	3
Supply chain risk	78	15	48.39%	3
Ce practices	78	4	12.90%	2
Case study	77	22	70.97%	2
Epidemic outbreaks	77	14	45.16%	2
Digital supply chain	72	13	41.94%	3
Impact of covid	69	17	54.84%	3
Emerging technologies	69	10	32.26%	2
Information sharing	66	18	58.06%	2
Sustainable supply chain management	64	13	41.94%	4
Supply chain visibility	64	11	35.48%	3
Logistics management	63	13	41.94%	2
Ai and bda	63	2	6.45%	3
Clean prod	61	2	6.45%	2
Sustainable scm	60	2	6.45%	2
Decision makers	58	13	41.94%	2
Research questions	57	21	67.74%	2
Ahead of print	57	8	25.81%	3
Resilient supply	56	16	51.61%	2

Table 2 Key phrases identified by WordStat from the dataset (F>30) (Con't)

PHRASE	FREQUENCY	NO. CASES	% CASES	LENGTH
Research agenda	55	19	61.29%	2
Internet of things iot	54	24	77.42%	4
Real time data	54	14	45.16%	3
Artificial intelligence	54	14	45.16%	2
Supply chain sustainability	52	17	54.84%	3
Covid crisis	52	16	51.61%	2
Sustainable performance	52	7	22.58%	2
Cyber physical	51	20	64.52%	2
Machine learning	50	18	58.06%	2
Data driven	50	17	54.84%	2
Global supply chains	49	18	58.06%	3
Data collection	49	14	45.16%	2
Digital twin	49	9	29.03%	2
Developing countries	48	12	38.71%	2
Production management	47	15	48.39%	2
Business model	47	14	45.16%	2
Social distancing	46	15	48.39%	2
Supply chain risk management	46	12	38.71%	4
Sustainable supply chains	46	11	35.48%	3
Environmental sustainability	46	11	35.48%	2
Enabler technologies	46	1	3.23%	2
Competitive advantage	45	15	48.39%	2
Operations research	45	12	38.71%	2
Enabling technologies	45	4	12.90%	2
Systematic review	44	16	51.61%	2
Food security	44	9	29.03%	2
Clean prod https	44	2	6.45%	3
Supply chain performance	43	15	48.39%	3
End to end	43	12	38.71%	3
Industrial revolution	43	12	38.71%	2
Industry enabled	43	2	6.45%	2
Disruptive technologies	40	10	32.26%	2
Business models	39	16	51.61%	2
Supply chain disruption	39	13	41.94%	3
Food supply chains	39	13	41.94%	3
Digital supply chains	39	7	22.58%	3
Sustainable production	38	13	41.94%	2
Ripple effect	38	9	29.03%	2
Supplier selection	38	6	19.35%	2
Supply chain operations	37	16	51.61%	3
Cleaner production	37	9	29.03%	2
Sc resilience	37	7	22.58%	2
Supply networks	36	13	41.94%	2
Information processing	36	12	38.71%	2
Information systems	36	11	35.48%	2
Green supply chain management	36	10	32.26%	4
Digital transformation	35	14	45.16%	2

Table 3 Key phrases identified by WordStat from the dataset (F>30) (Con't)

PHRASE	FREQUENCY	NO. CASES	% CASES	LENGTH
Agri food	35	11	35.48%	2
Post pandemic	35	11	35.48%	2
Short term	35	11	35.48%	2
Pythagorean fuzzy	35	3	9.68%	2
Smallholder farmers	35	2	6.45%	2
Small and medium	34	17	54.84%	3
Manufacturing industry	34	12	38.71%	2
Implementation of industry	34	11	35.48%	3
Buyer supplier	34	7	22.58%	2
Information management	33	12	38.71%	2
Decision support	33	10	32.26%	2
Dynamic capabilities	33	8	25.81%	2
Manufacturing companies	33	8	25.81%	2
Production processes	33	7	22.58%	2
Resource allocation	33	6	19.35%	2
Bda and ai	33	2	6.45%	3
Supply chain network	32	15	48.39%	3
Sars cov	32	15	48.39%	2
Research opportunities	32	15	48.39%	2
Business processes	32	13	41.94%	2
Annals of operations research	32	10	32.26%	4
Manufacturing processes	32	9	29.03%	2
Technologies of industry	32	5	16.13%	3
Epidemic outbreak	32	3	9.68%	2
Sc covid	32	1	3.23%	2
Base technologies	32	1	3.23%	2
Digital technology	31	17	54.84%	2
Information technology	31	16	51.61%	2
Operations and supply chain management	31	11	35.48%	5
Data analysis	31	11	35.48%	2
Natural disasters	31	11	35.48%	2
Supply chain processes	31	9	29.03%	3
Manufacturing industries	31	8	25.81%	2
Peer review	31	5	16.13%	2
Product customization	31	4	12.90%	2
Scres antecedents	31	1	3.23%	2
Capability building	31	1	3.23%	2
Triple bottom line	30	15	48.39%	3
Global supply chain	30	10	32.26%	3
Competitive advantages	30	8	25.81%	2
Areas of enhancements	30	1	3.23%	3
Continuous developments	30	1	3.23%	2
Work implications	30	1	3.23%	2

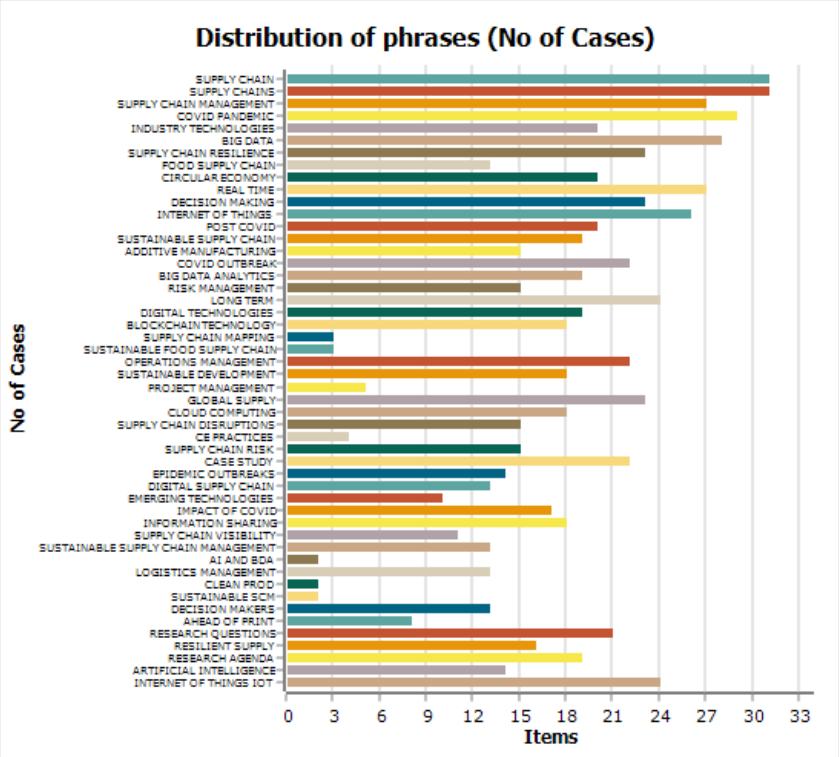

Figure 1 Bar chart showing most common phrases as analyzed by WordStat

Table 4 A list of topics and keywords as categorized by WordStat

Topic	Keywords	Coherence (npmi)	Eigen value	Frequency	Cases	% cases
Supply chain	Supply; chain; chains; resilience; covid; sustainable; food; digital; resilient; pandemic; management	0.190	2.54	8071	31	100.00%
Real time information	Time; supply; chain; ef; products; visibility; ciency; real; product; waste; improve; information; quality; costs; raw; materials; increase; transparency; cost; inventory; rm; reduce; processes; reduction; sharing; responsiveness; reducing; improves	0.166	3.03	3747	31	100.00%
Industry Technologies	Ce; industry; technologies; adoption; practices; sustainable; circular; economy; barriers; project; ssc; implementation; development; ef; competitive; company	0.241	2.65	2489	31	100.00%
Internet of Things	Internet; things; iot; cloud; computing; cyber; physical; technologies; data; big; additive; manufacturing; systems; analytics; blockchain; industry	0.335	3.22	2176	31	100.00%
Covid pandemic	Covid; social; distancing; health; equipment; food; pandemic; safety	0.210	2.60	1114	31	100.00%
Epidemic Outbreaks	Epidemic; outbreaks; allocation; outbreak; resource; disease; impacts; scs; coronavirus; covid; effects; disasters; pandemics	0.252	2.29	1009	31	100.00%

Table 5 A list of topics and keywords as categorized by WordStat (Con't)

Topic	Keywords	Coherence (npmi)	Eigen value	Frequency	Cases	% cases
Big data Analytics	Analytics; big; data; performance; capabilities; dynamic	0.152	2.12	794	30	96.77%
Decision Making	Decision; making; makers; data; selection; criteria; fuzzy	0.186	2.17	646	30	96.77%
Buyer Supplier Survivability of sscs	Buyer; supplier; survivability; enhancing; factors; relationship; relationships; identif ed; managing; signi; viability	0.383	2.23	492	30	96.77%
Competitive Business environment	Competitive; business; advantage; pandemic; smallholder	0.059	2.17	384	31	100.00%
Positive Effect	Positive; gscm; returns; effect; validity; performance; constructs; relationship	0.164	1.99	312	29	93.55%
Long term	Term; long; short	0.194	2.01	260	29	93.55%
Small and Medium Enterprises	Medium; small; enterprises	0.221	2.21	153	27	87.10%
Artificial Intelligence	Intelligence; artificial; robotics	0.323	2.09	134	25	80.65%

Using WordStat, the phrases were then categorized into topics that are relevant to the current investigation. The resultant categorization is as shown in **Table 2**, ranked according to the frequency of their associated key words in the body of the documents being analyzed.

It is important to note that after the initial loading of documents and automatic processing of the texts by WordStat, there was a round of data cleaning in which some unrelated phrases such as journal names, misspelt words, and general descriptors (e.g. DOI, HTTPS, author) were removed by putting them in the exclusion list in order to avoid confounding the data.

4. FINDINGS AND DISCUSSION

Generating findings from the identified codes and themes depended on a subjective analysis of the insights and sentiments implied in the documents. Based on the data analysis using content analysis there were three main findings to emerge from this research.

4.1 Finding 1: I 4.0 Impact on Supply Chain Resilience

The adoption of Industry 4.0 technologies such as artificial intelligence and the Internet of Things has had a significant impact on the resilience of supply chain management among firms in emerging economies during the COVID-19 pandemic. Companies that had implemented these technologies were able to quickly adapt to the changes in demand and supply disruptions caused by the pandemic. For example, Singh, Sharma and Rana (2022) and Marinagi *et al*. (2023) both highlight the positive impact of Industry 4.0 technologies on supply chain resilience, with Singh specifically emphasizing the role of Artificial Intelligence. Xu (2022) further explores this by designing simulation scenarios for an LED factory, demonstrating how Industry 4.0 technologies can enhance supply chain resilience. Soares *et al*. (2021) provides a practical application of these findings, evaluating the potential for Industry 4.0 technologies in the Brazilian Northeast automotive OEM industry post-COVID-19. These studies collectively underscore the potential of Industry 4.0 to improve supply chain resilience. Artificial intelligence and machine learning algorithms were used to optimize inventory management, predict demand and improve forecasting accuracy, reducing the impact of supply chain disruptions. The use of Internet of Things technologies such as sensors, RFID and GPS tracking, helped companies to track products, monitor supplier performance and make real-time decisions, which helped to minimize inventory shortages and stockouts (Raja Santhi and Muthuswamy, 2022). Dongfang *et al*. (2022), Hussain *et al*. (2021) and Agrawal *et al*. (2020) found that the use of digital platforms and automation also helped to reduce human errors and increase operational efficiency, leading to faster response times to disruptions and improved customer service. Schuster *et al*. (2021) note that leading companies are now seeking to use innovative capabilities to design supply chains that are cost-effective yet resilient, which has been shown to improve performance outcomes. The use of these technologies also helped to improve the resiliency of supply chain in emerging economies by increasing transparency, enabling better risk management and reducing the dependence on a single source of supply (Lopes de Sousa Jabbour *et al*., 2022; Raja Santhi and Muthuswamy, 2022). Moreover, these technologies helped to reduce the need for physical interactions, thereby reducing the risk of infections and enabling continuity of operations in the face of lockdowns and other restrictions (Hussain *et al*., 2021). Nandi *et al*. (2021), Joshi and Sharma (2022c) and Lopes de Sousa Jabbour *et al*. (2022) equally paint industry 4.0 as a critical mitigating factor for keeping important industries running. In conclusion, the findings suggest that the adoption of Industry 4.0

technologies has played a key role in helping emerging economies to weather the disruptions caused by the COVID-19 pandemic and maintain the resilience of their supply chain management.

4.2 Finding 2: Adoption and Effectiveness of I 4.0 in Emerging Countries was Constricted by Resource Constraints Compared to Developed Countries

The characteristics of emerging economies, such as limited infrastructure and a lack of technological proficiency, significantly influence the effectiveness of Industry 4.0 in enhancing supply chain resilience during the COVID-19 pandemic. For example, Acioli *et al*. (2021) and Farooq *et al.* (2021) present two parallel analyses that highlight the differences in supply chain resilience between developed and developing countries, respectively. Whereas Acioli *et al*. (2021) find Industry 4.0 to be a good fit for supply chains in developed countries where their analysis was based, Farooq *et al.* (2021) navigate their analysis by identifying various ways to implement Industry 4.0 amid the numerous challenges that exist in developing countries.
Resource constraints that characterize emerging economies such as inadequate transportation networks and a lack of reliable energy sources, can impede the implementation and use of Industry 4.0 technologies, making it difficult for companies to fully utilize the benefits of these technologies (Farooq *et al*., 2021; Piyathanavong *et al*., 2022; Raja Santhi and Muthuswamy, 2022). A lack of technological proficiency among employees and a shortage of skilled workers in emerging economies can also pose a challenge to the successful implementation and use of Industry 4.0 technologies. The limited access to financial resources and a lack of government support for the implementation of Industry 4.0 technologies also acts as a barrier for companies in emerging economies (Lu *et al*., 2022; Nur *et al*., 2022). Furthermore, the lack of data privacy and security regulations in emerging economies can also impede the adoption of Industry 4.0 as companies might be hesitant to share sensitive information (Mphela *et al*., 2022).

4.3 Finding 3: The Long-term Implications of I 4.0 Necessitated by COVID-19 are Multifaceted

The long-term implications of Industry 4.0 adoption on supply chain resilience in emerging economies post-COVID-19 are multifaceted and have both positive and negative effects. On one hand, Industry 4.0 technologies have the potential to help companies in emerging economies to better anticipate and respond to disruptions in the future by improving visibility and control over their supply chains and enabling real-time decision-making. The adoption of Industry 4.0 can also help to improve efficiency and reduce costs, through automation and optimization of processes, which can lead to a more competitive and sustainable supply chain in the long-term. Additionally, Industry 4.0 can also help companies in emerging economies to increase transparency and reduce dependence on a single source of supply, thereby improving the overall resilience of their supply chains (Kumar *et al*., 2022; Joshi and Sharma, 2022b; Piyathanavong *et al*., 2022; Reza *et al*., 2022; Samper *et al*., 2022).

On the other hand, the lack of investment in infrastructure and a shortage of skilled workers in emerging economies can impede the implementation and use of Industry 4.0 technologies, limiting the benefits that companies can reap in the long-term. This factor, as discussed by Samper *et al*. (2022) and Kumar *et al*. (2022) also ties with apprehension about loss of already scarce jobs due to technology replacing humans. Additionally, a lack of data privacy and security regulations in emerging economies can make companies hesitant to adopt Industry 4.0 technologies and it can also pose a risk to the security of sensitive information. As asserted by Lu *et al*. (2022) the long-term implications of Industry 4.0 adoption on supply chain resilience in emerging economies post-COVID-19 are complex and depend on various factors such as the level of investment, the availability of skilled workforce, and the regulatory environment. Companies in emerging economies should consider these factors when evaluating the adoption of Industry 4.0 technologies to ensure that they can fully leverage the benefits of these technologies in the long-term.
Overall, the research suggests that while Industry 4.0 technologies have the potential to enhance supply chain resilience during the COVID-19 pandemic, the unique characteristics of emerging economies can pose challenges to the successful implementation and use of these technologies. Therefore, it is important for companies in emerging economies to address these challenges by investing in infrastructure, training employees, and seeking government support to ensure that they can fully leverage the benefits of Industry 4.0.

4.4 Comparison of Findings with Other Studies

The results of this study are largely in line with those published in similar research efforts carried out in similar contexts around the impacts of the COVID-19 pandemic. For example, Joshi and Sharma (2022a) and Farooq *et al.* (2021) both emphasize as this research does that the use of industry 4.0 is the central pillar of ensuring global supply chain resilience. In general, there is consensus among the research studies that were sampled on the need for countries in the emerging world to fast-track their adoption of emerging technology as a tool for supply chain management. The slight points of departure relate to the exact way in which Industry 4.0 should be applied. For the larger part, the current study identified inventory management as the main area of utilization where Industry 4.0 needs prioritization. Other studies saw different areas of priority, for example, Nur *et al.* (2022) prioritized integration of technology in workforce skill development. On their part, Piyathanavong *et al.* (2022) view product customization as the most critical area of Industry 4.0 utilization for companies looking to gain a competitive advantage in times of crisis.

4.5 Implications and Contributions to Theory

The findings of this research have several implications for the resource-based view theory. The resource-based view theory suggests that a firm's internal resources and capabilities can provide a source of sustained competitive advantage (Joshi and Sharma, 2022a). The research

findings suggest that the adoption of Industry 4.0 technologies, such as artificial intelligence and the Internet of Things, can have a positive impact on the resilience of supply chain management in emerging economies during the COVID-19 pandemic. This can be seen as a sustained competitive advantage in the sense that the companies that adopt these technologies are better able to respond to disruptions and maintain continuity of operations, which is a critical aspect for companies to survive and even grow in a crisis situation like pandemics.

The research also highlights the limitations and challenges of the emerging economies in terms of limited infrastructure and a lack of technological proficiency. These challenges can be seen as constraints to the companies' resources and capabilities. Therefore, the research contributes to the resource-based view theory by providing empirical evidence that the availability and quality of resources and capabilities are critical factors for companies to fully leverage Industry 4.0 technologies and gain a sustained competitive advantage, as Kraaijenbrink *et al.* (2010) argue. The research suggests that companies in emerging economies should focus on developing the necessary resources and capabilities to take full advantage of Industry 4.0 technologies.

4.6 Implications and Contributions to Practice and Policy

The findings of this research have several implications for practice. The research suggests that the adoption of Industry 4.0 technologies, such as artificial intelligence and the Internet of Things, can have a positive impact on the resilience of supply chain management in emerging economies during the COVID-19 pandemic. This highlights the importance of investing in these technologies and building the necessary infrastructure and capabilities to take full advantage of them. Companies in emerging economies should focus on developing the necessary resources and capabilities to implement Industry 4.0 technologies, and to leverage these technologies to improve supply chain resilience.

Additionally, the findings of this research indicate that the characteristics of emerging economies, such as limited infrastructure and a lack of technological proficiency, can be a challenge for companies to fully leverage the capabilities of Industry 4.0. Therefore, companies in emerging economies should also focus on developing the necessary infrastructure and capabilities to fully leverage Industry 4.0 technologies.

The research also suggests that Industry 4.0 adoption has positive long-term implications on supply chain resilience in emerging economies post-COVID-19. Companies should consider adopting Industry 4.0 technologies to improve supply chain visibility, efficiency and flexibility, which will enable companies to more effectively navigate a rapidly changing business environment.

Overall, this research provides valuable insights into how Industry 4.0 technologies can be used to enhance supply chain resilience in emerging economies and has the potential to inform practice in this field. It suggests that companies in emerging economies should focus on developing the necessary resources and capabilities to leverage Industry 4.0 technologies, and to improve their supply chain resilience in the long run.

5. CONCLUSIONS AND RECOMMENDATIONS

The COVID-19 pandemic presented a good scenario for the demonstration of optimal resource utilization as a tool for SSCM. The findings of this research suggest that the adoption of Industry 4.0 technologies has had a significant impact on the resilience of supply chain management for firms in emerging economies during the COVID-19 pandemic. Companies that had implemented these technologies were able to quickly adapt to the changes in demand and supply disruptions caused by the pandemic, thereby reducing the impact of supply chain disruptions. The use of these technologies also helped to improve the resiliency of supply chain in emerging economies by increasing transparency, enabling better risk management and reducing the dependence on a single source of supply. However, the research also found that the characteristics of emerging economies, such as limited infrastructure and a lack of technological proficiency, have a significant influence on the effectiveness of Industry 4.0 in enhancing supply chain resilience. Resource scarcity, a major impediment to the implementation of resource-intense of industry 4.0 technologies stands in the way of full and optimal deployment of relevant technologies in developing countries.

Based on the findings of this research, the following recommendations are proposed for companies in emerging economies looking to leverage the benefits of Industry 4.0 technologies to enhance supply chain resilience:

1. Peer-to-Peer Collaboration: Collaborative initiatives can help overcome individual resource limitations and collectively navigate supply chain disruptions. Therefore, firms should seek to establish networks and consortiums with other local firms to share resources, knowledge, and best practices.
2. Resource Optimization: Firms in developing countries should ensure optimized and efficient utilization of available resources. This can be done through internal changes such as implementation of lean manufacturing principles, energy-saving measures and adoption of circular economy in raw material utilization.
3. Leverage government support: Companies should seek government support for the implementation of Industry 4.0 technologies, as limited access to financial resources and a lack of government support can be a barrier for companies in emerging economies.
4. Skill Development: By investing in training and skill development programs firms in developing economies can enhance the technical capabilities of the workforce. Developing skills in emerging technologies such as automation, data analytics, and IoT will enable firms to leverage Industry 4.0 tools effectively.
5. Long-term planning: Companies should consider the long-term implications of Industry 4.0 adoption on supply chain resilience in emerging economies post-COVID-19 and plan accordingly.

Overall, the research provides valuable insights into the role of Industry 4.0 technologies in enhancing supply chain resilience in emerging economies during the COVID-19 pandemic and the challenges that companies in these economies may face in implementing these technologies.

RESEARCH IMPLICATIONS

The findings imply that adopting these technologies can provide a sustained competitive advantage by enabling companies to respond to disruptions and maintain continuity of operations. However, limited infrastructure and a lack of technological proficiency in emerging economies can pose challenges to fully leveraging Industry 4.0 capabilities. Therefore, the research highlights the importance of investing in necessary resources and capabilities to take full advantage of these technologies and improve supply chain resilience. These findings can inform practice and policy in the field and provide valuable insights into the potential long-term implications of Industry 4.0 adoption on supply chain resilience.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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