Research developments in Sustainable Supply Chain Management considering Optimization and Industry 4.0 Techniques: A Systematic Review

Abstract

Purpose – The literature that is presently available on sustainable supply chain management (SSCM) combining Optimization and Industry 4.0 techniques falls short in its depictions of the recent developments, budding pertinent areas, and the importance of SSCM in the growth of industrial economies around the world. This article's main objective is to analyze current trends, highlight the latest initiatives, and perform a meta-analysis of the literature that is currently accessible in the SSCM area with a special focus on optimization and Industry 4.0 techniques. The paper also proposes a conceptual framework that will assist in illuminating how the ideas of optimization and Industry 4.0 may contribute to realizing sustainability in supply chains.

Design/methodology/approach – The proposed study systematically reviews 85 research publications published between 2010 and 2022 in referenced peer-reviewed journals in diverse fields, including engineering, business and management, services, and healthcare. Numerous categories are considered throughout the examination of the literature, including year-wise publications, prominent journals, type of research design, concerned industry, and research technique used.

Findings – The study demonstrates a deeper comprehension of the literature in the field and its evolution throughout numerous industry sectors, which is helpful for both practitioners and academics. The results from the content analysis highlight various future research opportunities in the domain.

Originality/value – This is one of the first research articles that have attempted to establish, analyse, and highlight the current trends and initiatives in the SSCM domain from an optimization and Industry 4.0 techniques viewpoint. The cluster-based future research propositions also enhance the novelty of the study.

Keywords*:* Sustainable Supply Chain Management; Optimization; Industry 4.0.

1. Introduction

Supply chain management is concerned with the movement of goods, finances, and information through all value chain phases, including suppliers, manufacturers, distributors, retailers, and consumers. Managing demand, product design and development, supplier management (Wu *et al.*, 2020), raw material procurement, production planning and control, warehouse management, inventory planning, supply chain network design, distribution management, and last-mile delivery management are all essential subsystems that are involved in supply chain

management. Within the system, elements such as risks (Munir *et al.*, 2020), disruptions, delays, and uncertainties significantly influence the performance of the supply chain.

Incorporating sustainable practices into a company's operations is necessary to remain relevant and thriving in today's market (Gracia and Quezada, 2016). The concept of sustainability refers to meeting the present generation's demands without jeopardizing future generations' capacity to meet their demands (Dumitrascu *et al.*, 2020). Social, economic, and environmental factors are the primary factors when we refer to sustainable supply chain management (SSCM).

In recent years, emerging technology has enabled organizations to address difficulties associated with supply chains in a manner that was impossible before. Despite this, companies are continuing their search for an effective balance of technology-driven solutions that would assist them in successfully adopting sustainability into their operations. Enabling factors for sustainable supply chain management include Industry 4.0 (I4) and optimization methodologies (SSCM). Even though various research (Hall *et al.*, 2012a; Souza *et al.*, 2019; Tautenhain *et al.*, 2019) have addressed the topic of sustainable supply chain management and the significance of the subject, relatively few of these studies have addressed the role that Industry 4.0 and optimization approaches play in sustainable supply chain management (SSCM).

Through an analysis of the current body of literature, this study aims to investigate the underlying trends and important research themes as well as the role that Industry 4.0 and optimization play in sustainable enterprises. In content analysis, we have presented future research views in the field by enumerating proposed research questions drawn from research gaps in the existing body of literature. In addition, one of our goals is to develop a conceptual framework that will assist in explaining how the ideas of optimization and Industry 4.0 may contribute to achieving sustainability in the supply chain.

This article is divided into seven sections, including one that serves as an ongoing introduction. The second part provides an overview of the historical context of the literature. The methodology used for our systematic review is discussed in the third section. In the next section (four), an analysis will be used to demonstrate the categorization of the articles that made the shortlist. In the fifth section, we present the cluster-based content analysis that outlines future research propositions. The sixth section offers the theoretical framework we developed based on literature classification and content analysis results. In the concluding part, we discuss the most important discoveries and our work's limitations.

2. Background of Literature on SSCM

This section will describe the theoretical backdrop of SSCM research, including optimization and Industry 4.0. It is crucial to optimize the supply chain since doing so may help businesses improve their efficiency, lower their expenses, and elevate the level of satisfaction experienced by their customers. Companies can optimize their supply chain processes, such as production

scheduling, inventory management, and transportation planning, with the help of mathematical modeling and algorithms (Nagurney and Nagurney, 2010). This allows companies to use resources more efficiently and improve their overall performance. In addition, optimization may assist businesses in recognizing and mitigating risks, such as interruptions in supply chain operations, and in coming to better-informed choices about future expenditures and growth (Sitek and Wikarek, 2015). Optimization may be a handy tool for establishing sustainability in the supply chain. Companies can optimize the processes in their supply chains via mathematical modeling and algorithms, which helps them have a more negligible effect on the environment, consume fewer resources and energy, and enhance their overall sustainability (Kaboli Chalmardi and Camacho-Vallejo, 2019). Optimization can be helpful for businesses, helping them become more profitable, competitive, and sustainable.

Table 1. Summary of past review-based studies in the SSCM domain

Authors	**Study focus**	**Study Type**
(Brandenburg and Rebs, 2015)	Analyzes past literature that formalizes issues related to SSCM in quantitative models	Review
(Borregan-Alvarado *et al.*, 2020)	Examines literature in the field of SSCM, keeping I4 and advanced manufacturing together	Bibliometric Review
(Dutta *et al.*, 2022)	Investigates the role of blockchain and the Internet of Things (IoT) individually on SSCM	Review
(Faramarzi-Oghani *et al.*, 2022)	Analyzes meta-heuristic algorithms applied in SSCM	Review
(Jayarathna *et al.*, 2021)	Investigates literature to assist in selecting suitable multi-objective optimization in SSC logistic modeling	Review
(Paul *et al.*, 2021)	Performs a systematic literature review for identifying various Multi-Criteria Decision Making (MCDM) techniques applied in the field of SSCM.	Systematic Literature Review
(Cañas *et al.*, 2020)	Conducts a review to assess the current state of knowledge of the supply chain from a sustainability perspective	Review

(Chalmeta and Santos-deLeón, 2020)	Analyzes the existing literature on sustainability, Industry 4.0, and supply chain management	Bibliometric Review

The term "Industry 4.0," which is often referred to as the "fourth industrial revolution," describes the incorporation of modern technologies such as the Internet of Things (IoT), big data, and artificial intelligence into the operations of manufacturing and logistics. Technologies from the fourth industrial revolution may play an essential part in achieving sustainability in the supply chain. These techniques enable businesses to improve the efficiency of their operations and make smarter decisions (Quariguasi Frota Neto *et al.*, 2010). For instance, innovations from Industry 4.0, such as the Internet of Things (IoT), may be used to track and control the energy used across the entire manufacturing process. This enables businesses to discover and cut down on waste and inefficiencies. By identifying the routes and modes of transportation that are the most time- and resource-effective, improvement of logistics operations and mitigation of the adverse effects of transportation on the environment are both possible with the help of technologies such as blockchain (Varriale *et al.*, 2021). Inventory management can be improved with artificial intelligence, which can also help reduce waste by ensuring that the appropriate inventory quantity is held at any given time.

Previously, several studies based on literature reviews have been carried out to add to the theoretical understanding of SSCM research. Table 1 contains information from previous research conducted in this field. To give a complete overview of the status of research in this field, we have also provided the study's focus. Although the earlier literature review studies provided an overview of SSCM research across specific parameters, they omitted the systematic literature evaluation over numerous parameters in a single study, which would be of great use to academics and practitioners. Additionally, there was no conceptual framework explaining how optimization and I4 applications fit into SSCM, presented based on a literature review.

3. Data and Methodology

The literature review is a crucial component of any research pursuit since it aids in assessing current trends and active areas in a particular field of research. This study employs a systematic approach to reviewing the existing, first screening the papers to be reviewed and then classifying and analyzing those articles to better understand the SSCM in the context of Optimization and Industry 4.0. A stepwise methodology for systematic literature review is shown in Figure 1.

3.1 Database and screening of articles

The fundamental objective of this study is to explore the research threads and advancements in the field of SSCM domain considering optimization and Industry 4.0 (I4) techniques. For this purpose, the Scopus database was chosen. We targeted all articles published in top peer-reviewed journals with the following keywords in their title and abstract, namely: “Sustainable

Supply chain Management," "Optimization," and "Industry 4.0". The search terms for this study produced 147 SSCM articles across 59 journals, which were further analyzed based on different perspectives through a classification framework. Articles featured during 2010–2022 were considered for review as the SSCM field started to gain popularity in the early 2000s. Subsequently, other documents such as conference papers, book chapters, editorial notes, and short notes were excluded during the screening stage. We also omitted documents from psychology, the arts, and neuroscience, and as a result, we obtained 104 documents. We then

reviewed the abstracts and screened the articles based on the scope of our study. We narrowed it down to 85 articles for our final literature review.

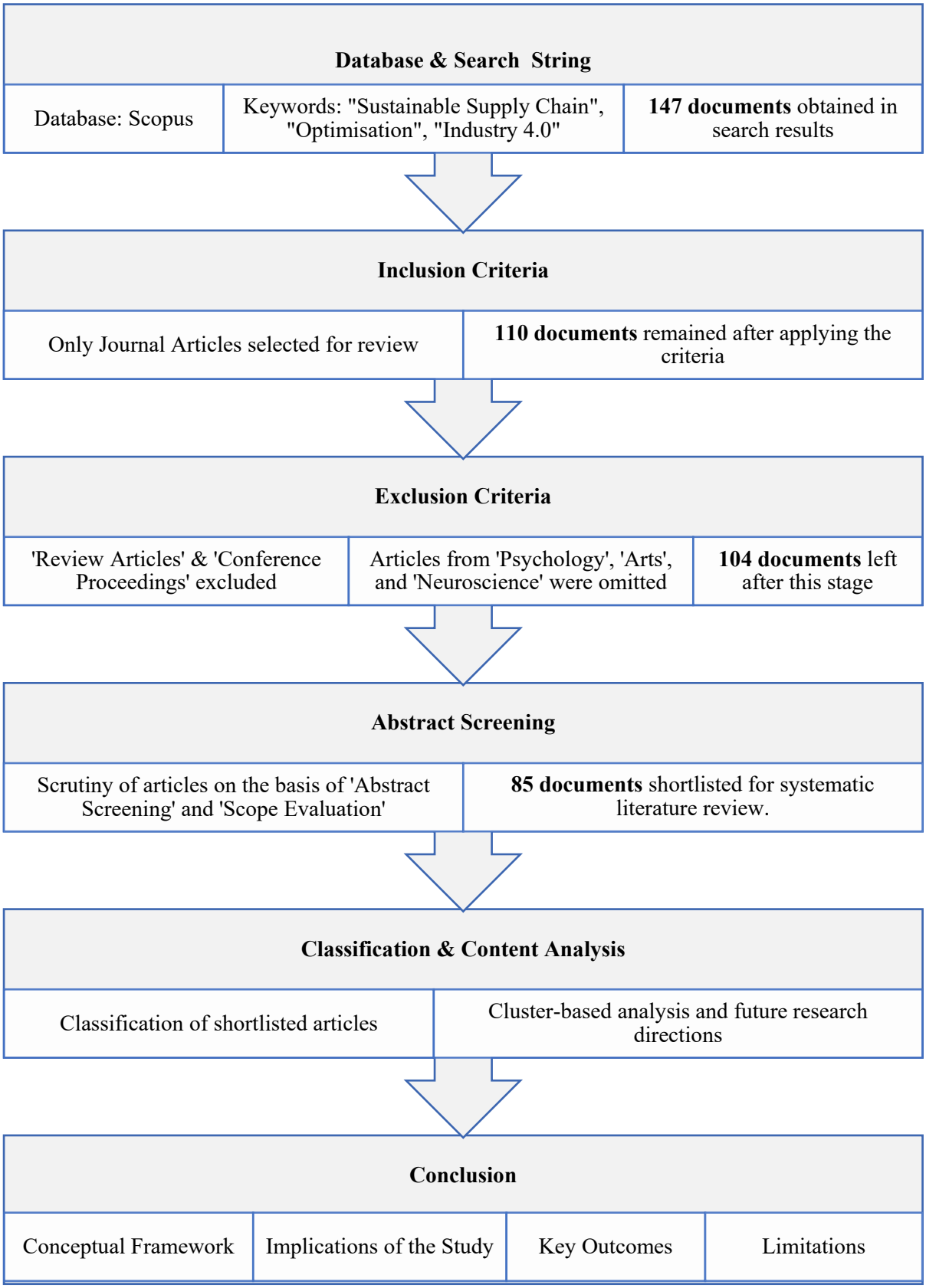

Figure 1 Methodology for Systematic Literature Review

The compilation of screened material includes research articles on an SSCM domain with several applications across diverse disciplines, including management, engineering, social sciences, health care, etc. Although the authors took care when choosing the final set of articles for the review, any pertinent article might have been left out. The authors believe the categorization framework, identified research themes, and analytical findings would be helpful to both scholars and practitioners.

3.2 Classification Criteria

Before beginning the evaluation of chosen research material, it is vital to specify the classification framework based on which the articles will be assessed. Consequently, for this study, we have analyzed the articles based on six broad categories that will facilitate a better grasp of research in SSCM coupled with Optimization and Industry 4.0 techniques. The study will also enable researchers and practitioners to investigate potential future research paths. The criteria for presenting research taxonomy are described below-

1. Year of Publication
2. Prominent Journals and Publishers
3. Country of Publication
4. Research Method Used
5. Industry under Consideration
6. Prominent Authors

This presented classification will help offer a roadmap for a thorough understanding of the field by providing promising research trends, sequential growth, noteworthy research sources, application areas, and exciting aspects of SSCM concerning optimization and industry 4.0 techniques.

Furthermore, we conducted a cluster-based content analysis of the selected documents. This analysis was backed by future research propositions for each cluster. Based on the results of the classification of research material and content analysis, we developed a conceptual framework that explains the integration of optimization and Industry 4.0 techniques to achieve sustainability in supply chain operations. We conclude our study by highlighting the key outcomes and limitations of the study.

4. Analysis of the Literature

4.1 Year-wise trend of publications

The variation of "Sustainable Supply Chain Optimization and Industry 4.0" articles based on the year of publication is indicated in Figure 2, spanning over 13 years (2010–2022). In the early phases, there is very low or no interest shown by researchers and practitioners when it comes to integrating optimization and I4 techniques with SSCM. Later around 2017, both developed and developing economies realized the importance of sustainability in supply chain operations and showed their willingness to integrate optimization and I4 techniques with sustainable supply chain management practices. Since 2017, the frequency of publishing articles has considerably increased. Reference to integrating optimization and I4 in SSCM may be found in the manufacturing (Yadav *et al.*, 2020), IT & services, food sector, healthcare (Daú *et al.*, 2019), and construction industries. Alongside these, it is notable that the number of SSCM publications has also increased significantly in several other disciplines.

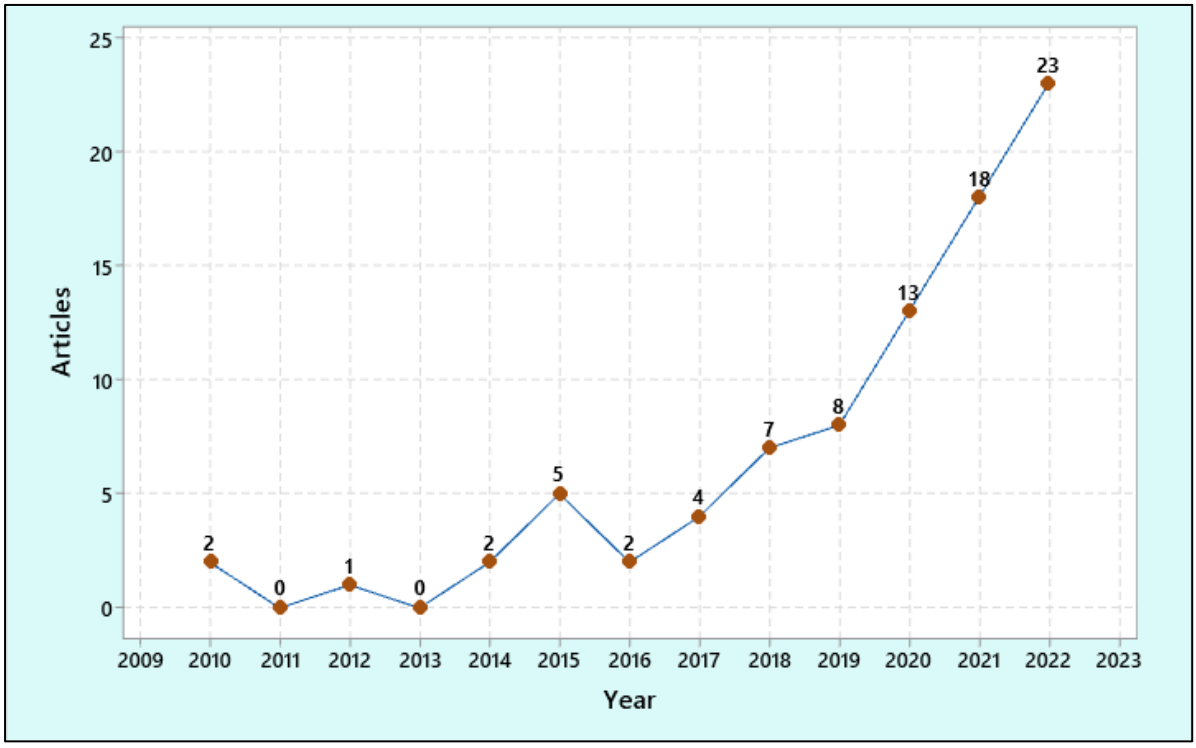

Figure 2 Year-wise trend of publications

4.2 Top Journals and Publishers

When discussing optimization and I4 approaches in the context of SSCM, there are several journals from diverse areas such as engineering, computer science, management, decision-making, and services. Among these esteemed indexed journal sources, the Journal of Cleaner Production has the most significant portion of articles (11.76%). This journal has continuously published a wide range of articles since 2010 to raise the degree of familiarity with the area among scholars and other stakeholders. The International Journal of Production Research has

obtained the second largest percentage (9.41%), indicating a reasonably high consideration of sustainability in manufacturing practices across industries.

Table 2 Classification based on journals and publishers

Sources	Publishers	h-Index	Articles	Percentage
Journal of Cleaner Production	Elsevier	232	10	11.76
International Journal of Production Research	Taylor and Francis	153	8	9.41
Sustainability (Switzerland)	MDPI	109	6	7.06
Computers and Industrial Engineering	Elsevier	136	6	7.06
Resources, Conservation, and Recycling	Elsevier	150	4	4.71
Annals of Operations Research	Springer	111	3	3.53
Advances in Intelligent Systems and Computing	Springer	48	2	2.35
Chemical Engineering Transactions	Italian Association of Chemical Engineering - AIDIC	39	2	2.35
Operations Management Research	Springer	31	2	2.35
Production Planning and Control	Taylor and Francis	85	2	2.35
International Journal of Logistics Management	Emerald Insight	80	1	1.18
European Journal of Operational Research	Elsevier	274	1	1.18
Business Strategy and The Environment	John Wiley	115	1	1.18
Computers and Chemical Engineering	Elsevier	144	1	1.18
Journal of Manufacturing Technology Management	Emerald Insight	76	1	1.18
Electronics (Switzerland)	MDPI	49	1	1.18
EMJ - Engineering Management Journal	Taylor and Francis	39	1	1.18
Others	N/A	N/A	33	38.82
Total	N/A	N/A	85	100.00

Sustainability (Switzerland) is ranked third on the list with a 7.06% share of articles. In addition, the supply chains across various businesses have seen substantial investment in optimizing and digitizing processes, as evidenced by the fourth-highest proportion (7.06%) of SSCM research publications published in the Computers and Industrial Engineering Journal. It is followed at places five and six by Resources, Conservation, and Recycling (4.71%) and Annals of Operations Research (3.53%). In Table 2, we have provided a detailed breakdown of how reviewed publications are categorized depending on journals and publishers.

However, when we talk about the publisher-wise distribution of articles, Elsevier contributed the maximum number of articles (31%) in the SSCM field, followed by Taylor & Francis (11%), SpringerLink (12%), Emerald Insight (8%), MDPI (8%) and Inderscience Publishers

(2%). The involvement of these publishers can be examined using Figure 3. A vast range of research areas under the SSCM field was discovered through the literature search from these publishers.

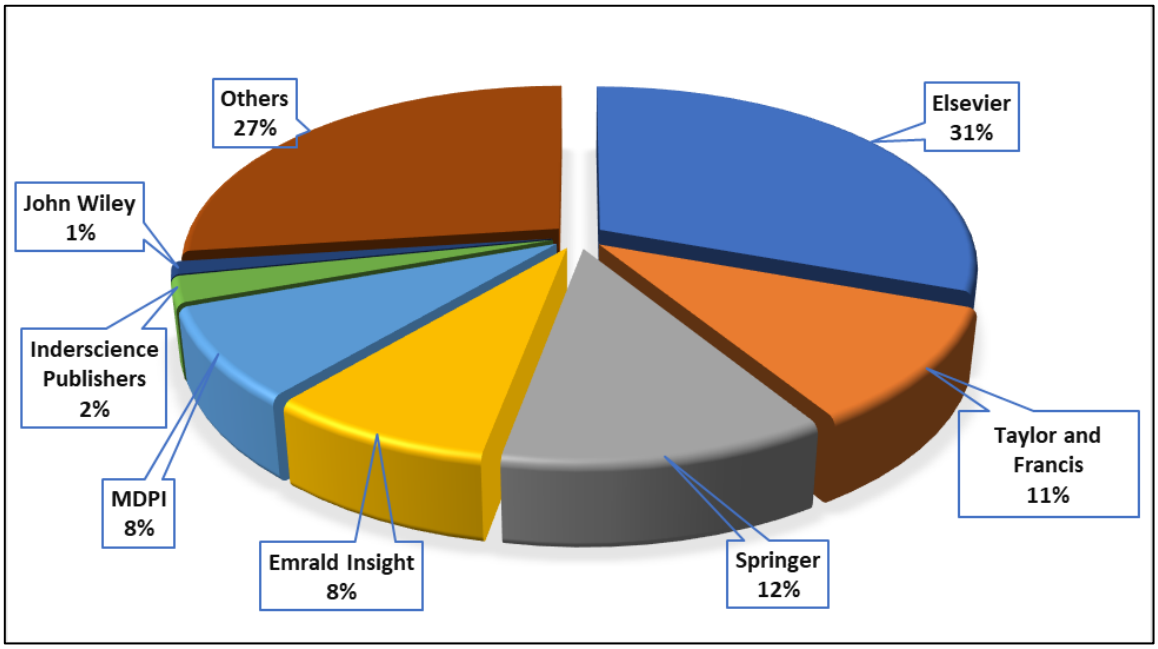

Figure 3 Pie chart-based distribution of publishers

Elsevier (Martín-Gómez *et al.*, 2019; Vivas *et al.*, 2020) included documents in various fields, primarily engineering, services, management, and manufacturing. The main topics addressed by different academics in SpringerLink (Rizzoli *et al.*, 2015; Zeng *et al.*, 2022a) include conceptual foundation-based papers impacting manufacturing sectors and survey-centric and framework-based publications. Articles from Taylor & Francis (He *et al.*, 2021) publications are primarily case study-based techniques covering service and safety-related issues. In contrast, Emerald Insight's publications focused mainly on the manufacturing and process industries. However, many papers tried to integrate optimization and industry 4.0 methodologies into the knowledge of sustainable supply chains.

4.3 Distribution based on country of publication

The study of the shortlisted articles demonstrates that the SSCM research, optimization, and Industry 4.0 have extensive publishing coverage in 25 countries worldwide. Table 3 indicates a thorough breakdown of research articles based on the country. China, with a total of 13 publications, has produced most of the research in the field among the 85 documents that were selected. In addition to India, Brazil, Iran, the UK, Korea, Turkey, and the USA are the prominent nations that contribute to synthesizing and reinforcing the theoretical underpinnings of SSCM research work incorporating optimization and industry 4.0. At the same time, the adoption of Optimization and Industry 4.0 in the context of SSCM was found to be extremely low in several countries, including Greece, Morocco, Netherlands, Switzerland, and Thailand.

However, there are many scenarios for SSCM research in various developing countries. These are considered outsourcing destinations because they can provide an affordable workforce, which is the most crucial component of supply chain planning. China, India, and Brazil provided 31% of all research publications. China and India (Hei et al., 2019; Yadav, Kumari, and Kumar, 2021) made the most extensive contributions to building a theoretical foundation and case study-based studies in SSCM; on the other hand, Brazil & UK made the largest contributions to quantitative applications, including mathematical and optimization-based studies. The groundwork for the implementation of optimization and I4 techniques in SSCM was developed with the aid of research articles from China and the UK.

Table 3 Country-wise breakdown of articles

Country	Articles	Percentage	SCP	MCP
China	13	15.29	9	4
India	8	9.41	5	3
Brazil	5	5.88	2	3
Iran	5	5.88	2	3
United Kingdom	5	5.88	2	3
Korea	4	4.71	2	2
Turkey	4	4.71	2	2
USA	3	3.53	3	0
Canada	2	2.35	1	1
France	2	2.35	0	2
Germany	2	2.35	1	1
Italy	2	2.35	2	0
Mexico	2	2.35	1	1
Poland	2	2.35	2	0

Portugal	2	2.35	2	0
Spain	2	2.35	2	0
Australia	1	1.18	0	1
Bulgaria	1	1.18	1	0
Colombia	1	1.18	1	0
Denmark	1	1.18	0	1
Greece	1	1.18	1	0
Morocco	1	1.18	1	0
Netherlands	1	1.18	0	1
Switzerland	1	1.18	1	0
Thailand	1	1.18	0	1
Total	85	100.00	50	35

SCP- Single Country Production; MCP- Multiple Country Production

4.4 Research Method Used

We have analyzed and noted the research method used for each shortlisted article. The research methods used in the literature include case studies, surveys, mathematical models, conceptual and theoretical models, interviews, other research methods such as systematic literature review, and industry focus. The distribution of research articles based on the research method is shown in Figure 4. From the analysis, it's evident that case study-based papers have got the highest contribution. It's intriguing to see that industry practitioners and academic researchers have expressed a strong concern in thoroughly examining the case applications within these case studies. As the primary research method, case studies are used in about 27% of papers, followed by articles based on mathematical models (21%) and conceptual model studies (17%). Even though conceptual models are found in 17% of the studies, there is a vast scope for improvement in this area because there is no standard model for optimization and I4 implementation in SSCM. Researchers may create a model by combining optimization with I4-based decision-making strategies.

Several situations (Quariguasi Frota Neto et al., 2010b; Tsai et al., 2021) described in the literature illustrate the advantages of adopting optimization and I4 methods by integrating decision-making methodologies. Other studies (Barbosa-Povoa *et al.*, 2018) have contributed to the development of the theoretical underpinning and frameworks that are equally useful for practitioners and researchers.

CS- Case Study; MM- Mathematical Model; CM-Conceptual Model; SV- Survey; IT-Interview; OT-Others

4.5 Industry under consideration

Every study looks incomplete until its applications are evident and it helps the growth of the national economy. The contribution of industries to a nation's economy is of crucial importance. Similarly, it becomes critical to find the applications of optimization and I4 in SSCM across various businesses.

This evaluation will encourage industry practitioners to implement optimization and I4 strategies inside their process system to achieve organizational sustainability. According to the categories in the preceding subsections, it is possible to conclude that case study-based studies are of great relevance to academics. The sector-wise distribution of selected research material is shown in Table 5.

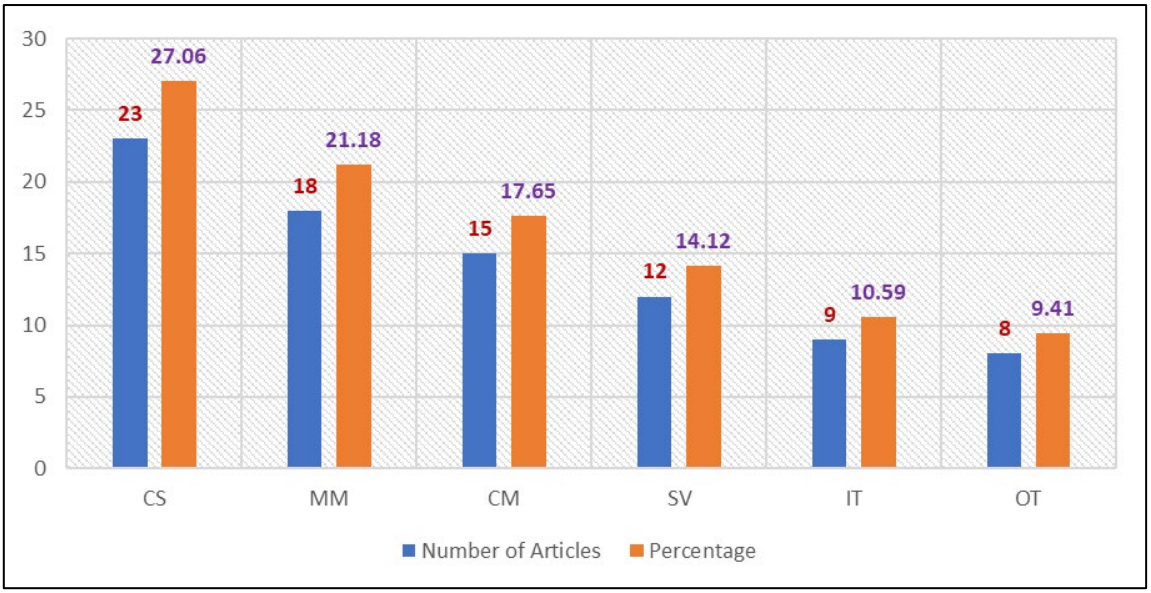

Figure 4 Classification based on the research method used

The manufacturing industry has the most considerable number of published case application articles, followed by the food industry and the IT & services sector. Practitioners of the modern supply chain are confronted with obstacles such as shorter product life cycles, rapid delivery needs, and sustainable product design and disposal. In addition to these industries, the

healthcare, pharmaceutical, process, electronics, and construction sectors have profited from using optimization, and I4 approaches in SSCM.

Table 5 Industry-wise distribution

S. No.	Industry Sector	Number of Articles
1	Manufacturing	15
2	Food Industry	13
3	IT & Services	10
4	Healthcare	9
5	Pharmaceutical	8
6	Process	7
7	Electronics	7
8	Construction	6
9	Textile	4
10	Others	6

4.6 Prominent Authors

For every classification study, it is critical to learn about the authors actively adding to the knowledge through their research. An early-stage researcher might find exploring a specific domain's most renowned research undertakings and perspectives very challenging. Therefore, it would be simpler for the new generation of researchers to investigate the most prominent studies published by the top authors, which could be identified. They can also utilize it to uncover new research ideas as well. A total of 293 writers accounted for 85 articles analyzed in the current literature review. Here by ‘author,’ we mean authors as well as co-authors.

Table 6 highlights the list of top authors contributing to SSCM research considering optimization and I4. Among these contributors is Barbosa-Povoa AP, with a total of 4 articles leading the list of researchers who helped create the theoretical basis, application-oriented studies, and conceptual framework. Zhang Y also sits at the top, contributing four articles in

almost all research dimensions. Further, Bui T-D, Lim MK, Mota B, and Tseng M-L are among the top contributors with high research credentials.

Table 6: Most Prominent Authors

Authors	Articles	h-index	i10-index
Barbosa-Povoa AP	4	58	157
Zhang Y	4	31	38
Bui T-D	3	13	15
Lim MK	3	17	20
Mota B	3	9	6
Tseng M-L	3	76	255
Carvalho A	2	61	260
Chan FTS	2	5	3
Ehtesham Rasi R	2	7	7
Gao J	2	62	146
Govindan K	2	112	296
Gunasekaran A	2	135	461
Guo Y	2	62	253
Kumar N	2	105	526
Kumari R	2	14	19
Lewi S	2	80	147
Lin C	2	71	167

Liu W	2	15	15
Mangla SK	2	62	128
Nascimento MCV	2	16	19
Sarkar B	2	58	199
Sitek P	2	16	20
Tautenhain CPS	2	4	2

5. Content analysis

After comprehensively classifying screened articles, we describe the literature through a cluster-based content analysis. Our content analysis was built around three major clusters- Optimization, Industry 4.0, and Sustainability aspects. In each cluster, we summarized the contributions of the most cited documents and proposed future research questions under each cluster.

5.1 Cluster 1: Optimization

Optimization techniques such as multi-objective optimization, stochastic programming, linear programming, supply chain network design, and route optimization have helped businesses cut costs and improve their performance. We identified 45 documents under this cluster.(Govindan *et al.*, 2014), which has received 434 citations, developed a multi-objective optimization model that integrates sustainability in decision-making for distribution in a perishable food supply chain network. The proposed technique aims to optimize environmental and economic objectives in a perishable food supply chain network by assessing the number and location of facilities and optimum products delivered to downstream stages and routes at each level. Additionally, the article offers a novel multi-objective hybrid technique called MHPV that integrates two recognizable multi-objective algorithms (MOPSO and AMOVNS) to solve the problem. The study results imply that the proposed MHPV technique achieves better results than other methods. (Mota *et al.*, 2018), with 101 citations, proposed a standard model for planning and designing closed-loop sustainable supply chains. It also considers interrelated problems such as facility location, supplier selection, capacity determination, purchase levels definition, intermodal and unimodal transportation network options, technology selection and allocation, supply planning, remanufacturing, and product recovery. The authors have addressed three dimensions of sustainability through objective functions like Life Cycle Analysis methodology, Net Present Value, and GDP-based metric. (Liu *et al.*, 2021), which received 29 citations, presents an integrated model which solves the location-inventory-routing problem for perishable products considering carbon emissions, economic cost, and product

freshness. The authors have developed a multi-objective planning-based model with constraints based on the real location-inventory-routing scenario. Table 7 shows the identified research gaps and corresponding future research propositions.

Table 7 Proposed research questions enumerated from cluster 1.

Research Gap	Proposed Research Questions (PRQs)
1. No studies have been conducted to compare the performance of different multi-objective optimization algorithms for sustainable supply chain network design.	• How does the performance of different multi-objective optimization algorithms vary for sustainable supply chain network design?
2. Optimization models should incorporate other aspects of social sustainability for the design and planning of a sustainable supply chain.	• How can factors such as labor rights and human capital development, be incorporated into the sustainable supply chain network optimization model?
3. Consider some additional factors in the optimization model concerning decisions on location inventory routing in the supply chain of perishable products.	• What is the effect of factors such as customer demand and product availability in optimizing the location inventory routing process? • What is the effect of vehicle speed on carbon emissions and economic cost in perishable goods supply chain operations?

5.2 Cluster 2: Industry 4.0

This cluster highlights the application of Industry 4.0 techniques in the context of SSCM. A total of 40 documents were identified under this cluster. (Manavalan and Jayakrishna, 2019), with 376 citations, proposed a framework for reviewing the preparedness of supply chain organizations from numerous perspectives to fulfill the conditions of Industry 4.0 transformation. The article also emphasizes the significance of sustainability and technology deployment, such as the Internet of Things, in attaining organizational goals. (Mastos *et al.*, 2020), which attracted 85 citations, demonstrates the impact of an Internet of Things-based solution on sustainable supply chain management (SSCM) performance. It also investigates how implementing a state-of-the-art industry 4.0 technique can improve sustainability both at the organization and supply chain levels. The study attempts to bridge the gap between

theoretical advancements and real-world application cases concerned with Industry 4.0 and sustainable supply chain management.

With 42 citations, (Jiao *et al.*, 2018), suggest data-driven techniques to facilitate a robust closed-loop supply chain design that alleviates greenhouse gas emissions and uncertainties in the system. The authors developed two models - an adaptive robust model (ARO) and a distributed robust optimization model (DRO) - for designing waste disposal facilities and carryings of closed-loop supply chains. (Balaman *et al.*, 2018), which has obtained 40 citations, developed an innovative bi-level decision support system (DSS) to assist the optimization and modeling of multi-product, multi-technology supply chains and co-modal transportation networks for biomass-based production, uniting two multi-objective optimization models. The authors designed a regional supply chain transportation network utilizing the UK's complete West Midlands (WM) region as a testing space to investigate the feasibility of the proposed solution methodology and solutions. They also conducted sensitivity and scenario analyses to deliver further comprehension into the optimization and design of biomass-based supply chains. Table 8 highlights the identified research gaps and corresponding future research questions.

Table 8 Proposed research questions enumerated from cluster 2.

Research Gap	Proposed Research Questions (PRQs)
1. Few studies evaluate the business's readiness for adopting Industry 4.0 for sustainable supply chains.	• What criteria should be used when assessing a company's readiness for Industry 4.0 transformation, and how could those criteria vary depending on different industries or organizations?
2. The existing literature provides little or no insights into potential challenges or risks associated with implementing Industry 4.0 technologies on an industrial scale.	• What challenges or risks are associated with implementing Industry 4.0 techniques in medium- and large-scale industries?
3. There is a lack of understanding regarding which data-driven approaches would work best when dealing with multi-uncertainties such as buyers' expectations, demands, and recovery uncertainties in a closed-loop supply chain.	• Which data-driven approaches would work best when dealing with multiple uncertainties in a closed-loop supply chain?
4. There is a need for an effective decision support system (DSS) that can aid in	• How to incorporate sustainability in a decision support system that aids in

modeling and optimizing multi-technology, multi-product supply chains, and co-modal transportation networks while considering economic and environmental considerations within the same framework.	modeling and optimizing multi-technology and multi-product supply chain operations?

5.3 Cluster 3: Sustainability aspects

Major themes under this cluster include social, economic, and environmental sustainability, circular economy, energy conservation, and Greenhouse gas (GHGs) monitoring and control. 85 documents in the literature discussed these themes of sustainable supply chain management. (Jabbarzadeh *et al.*, 2018), with a maximum of 155 citations in this cluster, provided intuition into the interplay between sustainability and resilience in supply chains. The article distinguishes tactics that businesses can utilize to enhance their performance in both aspects. The study underlines the importance of information sharing and collaboration among supply chain stakeholders. With 111 citations, the article by (Kumar *et al.*, 2017) demonstrated how to optimize orders among suppliers while factoring in all three dimensions of sustainable performance. They devised a methodology for assessing various aspects such as lead time, quality, cost, waste minimization, energy usage, social contribution, and emission utilizing fuzzy AHP. The authors proposed a fuzzy multi-objective linear programming technique allocating orders among suppliers.

(Zhang *et al.*, 2014), with 91 citations, recommended a framework that aids decisions concerning supply chain planning, design, and expansion problems, and visibly computes the trade-offs between environmental, economic, and responsiveness performance. The recommended framework facilitates us in deciding trade-off interactions between different objectives such as GHG emissions, total cost, and lead time. The framework was verified in an industrial test case via real-world data extracted from a Dow Chemical organization. The results revealed visible trade-offs between the three distinct objectives.

(Dubey *et al.*, 2015), which accounted for 74 citations, developed a responsive, sustainable supply chain network that can react to a handful of degrees of uncertainty due to unavoidable forces. The study shows a comparative analysis that is based on three formulations performing different parameter-sensitive analyses and test scenarios in terms of CPU time, final output, degree of closeness towards the ideal solution, level of conservatism, degree of satisfaction, and degree of balance involved in developing a compromise solution. (Yadav, Kumari, Kumar, *et al.*, 2021), with 57 citations, developed an SSCM model that considers carbon emissions and wastage reduction. The article proposes an optimization technique to attain the optimal values of batch size, production rate, preservation investment, and the number of shipments to maximize the total profit of the system. The study also identifies potential product combinations that can lead to profitability based on the cross-price elasticity of demand. Table 9 underlines this cluster's identified research gaps and respective future research questions.

Table 9 Proposed research questions enumerated from cluster 3.

Research Gap	Proposed Research Questions (PRQs)
1. There is a lack of understanding about how resilience and sustainability interact with each other in the context of the supply chain.	• How do resilience and sustainability interact in a supply chain environment? What is the industry-wise comparison between these two dimensions?
2. There is no discussion on how different businesses and countries have adopted sustainable supply chain management practices.	• What strategies should companies employ to ensure sustainability across their value chain?
3. Future studies should focus on developing new indicators to help quantify sustainability performance more accurately in a supply chain.	• What are the potential indicators to quantify sustainability performance in a supply chain?
4. There is limited exploration of environmental and social dimensions regarding large commercial corporations' sustainability initiatives.	• How to simultaneously integrate sustainability's environmental and social dimensions into large-scale commercial businesses?
5. More data must be collected regarding the effects of preservation technology investments on reducing waste in large-scale businesses.	• What is the effect of preservation technology investments on reducing waste in large-scale businesses?

6. Discussion

6.1 Conceptual Framework

After presenting a comprehensive classification of the research material, and cluster-wise content analysis, we propose a conceptual framework, as shown in Figure 5. This framework helps in understanding the outcomes of the use of Industry 4.0 and optimization techniques which later directs toward achieving sustainability in supply chain management.

Frequently occurring themes coming under Industry 4.0 cluster include Artificial Intelligence (Ethirajan *et al.*, 2020) & Big Data Analytics (Jain *et al.*, 2022), Internet of things (IoT)

(Manavalan and Jayakrishna, 2019), Blockchain (Mangla *et al.*, 2022), Digitalization (Belhadi *et al.*, 2022) and Data-driven decision-making (Zhang *et al.*, 2017).

Similarly, the other 'optimization' cluster includes articles discussing the application of techniques such as Linear Programming (Lee and Chung, 2022), Stochastic Modeling (Fattahi et al., 2021), Fuzzy Mathematics (Tseng *et al.*, 2021), Multi-objective optimization (Abbassi *et al.*, 2022; Tautenhain *et al.*, 2021), Supply Chain Network Design (Sundarakani *et al.*, 2021), Spatially Explicit Modeling, and Route optimization (Peng *et al.*, 2022).

The adoption of optimization and Industry 4.0 techniques have offered numerous advantages to businesses, some of which include- monitoring and control of the use of resources in production processes, smart and efficient logistic operations (Esmaeilian *et al.*, 2020), transportation planning to reduce carbon footprint, and efficient use of raw materials and energy in production processes (Sarkar *et al.*, 2021), smart inventory management. Our analysis also suggests that the use of optimization and I4.0 techniques has contributed to the areas such as environmental, social & economic sustainability (Hall *et al.*, 2012b), circular economy (Kazancoglu *et al.*, 2021; Mahroof *et al.*, 2021; Mishra *et al.*, 2023), closed-loop supply chain (Bisheh *et al.*, 2018), energy conservation, life cycle assessment (Gao and You, 2017), and Greenhouse gas (GHGs) emission monitoring & control (Zeng et al., 2022b). This is a testament that optimization and Industry 4.0 are potential enablers for achieving sustainability in supply chain operations.

6.2 Theoretical and Managerial Implications

This study extensively reviews the existing sustainable supply chain management literature at the interface between optimization and Industry 4.0 techniques. The trend analysis revealed that it is a growing research area and continues to be a major field of work for researchers. The further country-specific analysis highlighted that Asian countries are leading the research in this domain while European and some African countries are underrepresented. The cluster-wise content analysis results revealed ample opportunities for researchers to explore in the future. The proposed research questions identified under each cluster can potentially become a starting point for future studies in the field.

Furthermore, a conceptual framework that explains the types and optimization and industry 4.0 techniques that have helped businesses incorporate aspects of sustainability into their businesses was proposed. This framework will guide policymakers and stakeholders in decision-making and resource allocation. Intending to review the existing literature thoroughly, this piece of work derives valuable insights into financial literacy. Overall, this study serves as a reference excerpt of major trends, key themes, directions for future research, and a theoretical guideline for exploring research on integrating optimization and Industry 4.0 for sustainable supply chain management (SSCM).

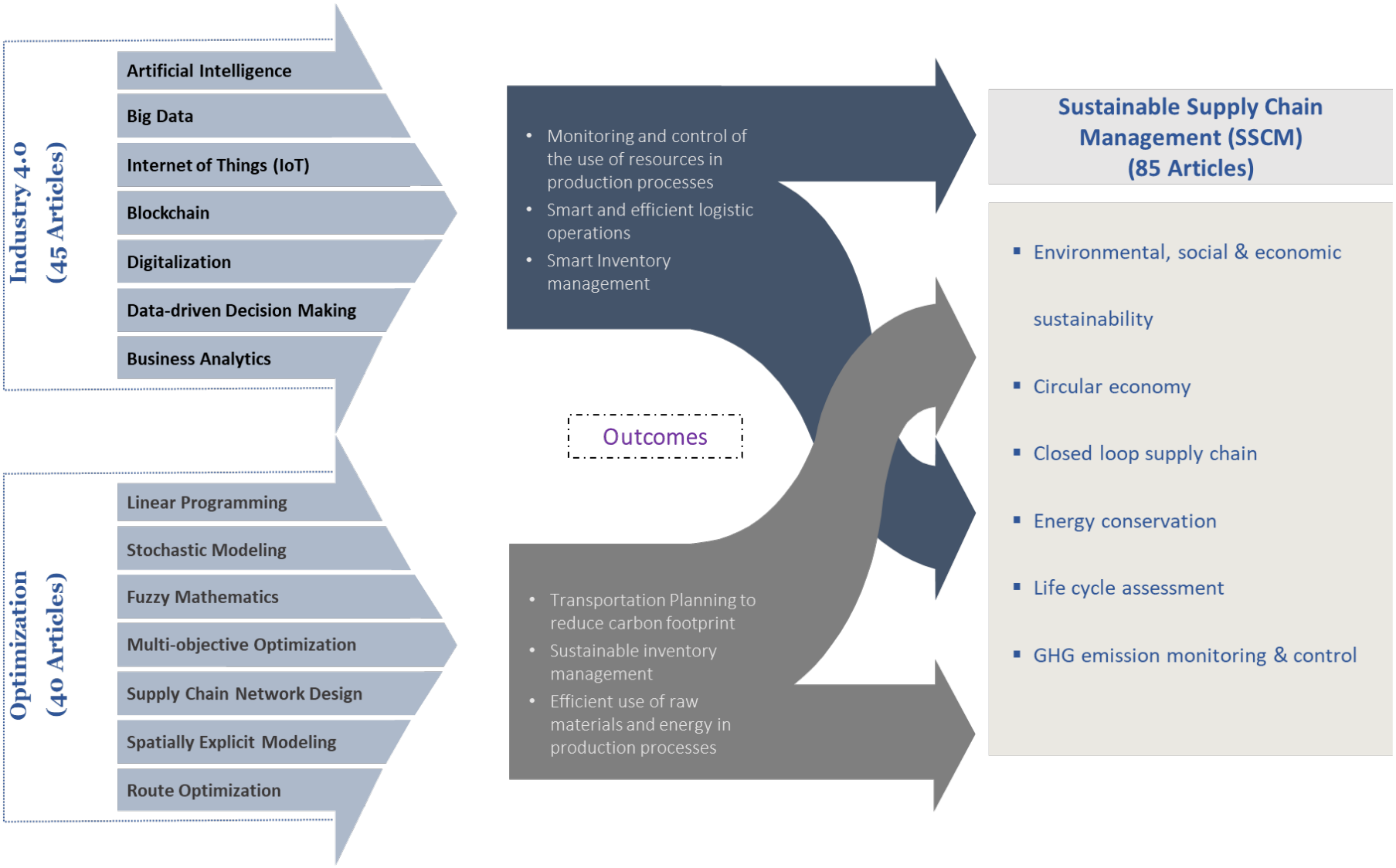

Figure 5 Framework for the use of optimization and Industry 4.0 techniques in SSC

7. Conclusion

7.1 Key Outcomes

One of the key goals of this study was to conduct a systemic literature review of existing literature that examines the use of optimization and I4 techniques in sustainable supply chain management. We investigated research articles from 2010 to 2022 in the Scopus database. Then we performed a screening of available literature based on numerous parameters, and finally, we were left with 85 documents which we analyzed for further literature evaluation. These 85 articles were then put under scrutiny based on several classification categories. The prominent highlights of the classification include the following- there has been a remarkable growth of research in the area since the year 2017; the Journal of Cleaner Production, and International Journal of Production Research and Sustainability are among the top sources of publications in the area, similarly if we talk about the countries, developing economies such as China, India, and Brazil are leading the chart and case study based articles are highest when we speak about classification based on research method. After presenting this classification, we have developed a conceptual framework explaining how optimization and I4 techniques enable businesses to incorporate sustainability into their supply chain operations. The proposed classification study and the developed framework will be helpful for practitioners and researchers belonging to all areas since it underlines the best practices in the context of applying optimization and I4 in SSCM. Given the massive growth of research in the area, we also believe there are numerous research opportunities that researchers can explore in the future.

7.2 Limitations

Future research pursuits require the studies to add to the body of knowledge. Still, at the same time, they are expected to align with existing studies while contributing to identified research gaps. We believe the three sustainability dimensions- social, economic, and environmental- are not new to researchers or practitioners. Still, it's necessary to remember that we need to incorporate the balance between these three dimensions while pursuing our future research.

This study attempts to explain the recent advances in sustainable supply chain management research with particular attention to optimization and industry 4.0 techniques. We have classified our shortlisted research articles based on year of publication, top journals and publisher, country of 1st author, the research method used concerned industry, and most contributing authors to develop a better understanding of the area. This study will facilitate the practitioners to undertake and redirect their future research better. Despite our best efforts, this study comes with its own set of limitations which we have described below -

- We have obtained the articles for our study using search keywords such as 'optimization,' 'industry 4.0', and 'sustainable supply chain.' This is quite possible that we missed some of the articles which do not have these keywords in the title or abstract but still talk about these themes.

- We have not used several categories of classification, such as top affiliations, classification based on the research design, etc. These can be included in future studies.

- The presented framework is based on the classification results in findings and our understanding of the research material. This framework can be subjected to testing and validation in future research endeavors.

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