

A Bibliometric Analysis of the Logistical Challenges and Methods for Vaccine distribution under the Pandemic

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Abstract. With the emergence and the widespread of the COVID-19 pandemic across the globe, there is an urgent need to effectively control the disease spread through mass vaccination. Several COVID-19 vaccines, e.g., Pfizer/BioNtech and Moderna, etc., have been proven highly effective and have been distributed and administrated in many countries. These vaccines need to be produced in large quantities and transported through dedicated cold chain logistic networks to maintain the quality. Currently, the major logistical challenges are associated with the effective distribution of COVID-19 vaccines to hospitals and healthcare centers in different countries. To better understand and tackle these challenges, we conduct a bibliometric analysis on vaccine supply chains and cold chain logistics for vaccine distribution. The current research landscape is investigated through four main classification analyses including journal co-citation analysis, keyword co-occurrence analysis, country collaborations analysis, and document co-citation analysis. These analyses allow us to identify the publication trends, the most popular journals in this field, the collaborations between countries and to identify the key areas where most attention is given. Finally, the methods are summarized, and the future research opportunities for effective COVID-19 vaccine distribution are identified.

Keywords: Bibliometric analysis, vaccine supply chain, cold chain logistics, COVID-19, literature review

1 Introduction

From the end of 2019, the COVID-19 pandemic has swept the globe and caused a large number of infections and deaths, which has also dramatically affected the global health care systems, economies, and many industries. As of May 9th, 2021, over 150 million confirmed cases of COVID -19 have been recorded with more than 3.2 million associated deaths, according to the World Health Organization (WHO) [1]. Mass vaccination is considered the most effective way to control infectious disease transmission and to restore people's normal lives. Even though several COVID-19 vaccines, e.g., Pfizer/BioNtech and Moderna, etc., have been developed and used in many countries,

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there are still significant supply chain and logistical challenges to satisfy the unprecedented worldwide demands during the pandemic [2].

The vaccine supply chain is a complex system that includes the locations, storage equipment, vehicles, transport routes, and personnel for handling the vaccines from production to administration [3]. Due to the strict temperature requirements for vaccine storage and transportation, cold chain logistics plays the most important role in a vaccine supply chain to ensure the timely and effective connection between the vaccine manufacturers and the points of administration. This has put challenges in logistics infrastructures and operations, especially in developing countries [4]. In this paper, we perform a bibliometric analysis of the research related to vaccine supply chain and cold chain logistics from 2010 to 2020, which aims at understanding the research landscape and the methods developed in this field. Based on the results, four suggestions are given for future research to better tackle the logistical challenges for the effective distribution of COVID-19 vaccines.

2 Research Method and Data Collection

Bibliometric analysis is a comprehensive and rigorous statistical approach to analyze a large amount of research data and to uncover deep insights into a research area [5], and it has been used and has become increasingly popular in the logistics field [6]. Donthu, Kumar, Mukherjee, Pandey and Lim [5] identified the four major steps for performing a bibliometric analysis for a given research area, which include (1) defining the aims and scope; (2) Selecting the techniques; (3) Collecting the relevant data; and (4) analyzing and reporting the results, respectively.

Based on the aims and scope of this paper, we conducted a comprehensive literature search on November 20th, 2020 using the Scopus database. All the literature search was performed on this single day to avoid dynamic updates of the database. Two separate searches were conducted on vaccine supply chain and cold chain logistics, respectively. The results were filtered and combined after several search refinement and eligibility tests, as shown in Fig. 1. Two logical keyword chains were developed for the search, and the initial results yielded a total of 2362 records, where 1470 are related to vaccine supply chains and 892 are related to cold chain logistics.

These records were first limited to the research articles from journals to ensure the quality of the literature. Then, these documents were further refined to show recent papers from the last decade (2010-2020) published in English. A total of 1067 documents remained after this initial refinement. These documents were then subjected to an inclusion and exclusion criterion filter in the subject area. Since the research focus of this paper is within vaccine logistics, supply chain, and operations management, the relevant papers in engineering, computer science, mathematics, decision sciences, energy, material sciences were thus included. On the other hand, the publications in veterinary, animal sciences, food sciences, agriculture sciences, dentistry, immunology, social sciences, neuroscience were excluded.

After this stage, 176 records were left and were screened by titles and by reading the abstracts. Herein, the keywords were defined to include "cold chain", "cold chain logistics" or "vaccine supply chain" in order to select the most relevant papers. After a careful reading, the articles that had none of these keywords in their titles and abstracts were excluded. Also, the topics focusing on vaccine development, vaccination and immunization, risk assessment, fresh foods cold chain, aquaculture cold chain were excluded. In this stage, 57 articles were eliminated, and the other 119 articles were thus selected for the analysis. There were no duplicate articles found when these 119 articles were exported into the Endnote reference manager for duplication checks. Therefore, a total number of 119 articles were used for the bibliometric analysis in this paper.

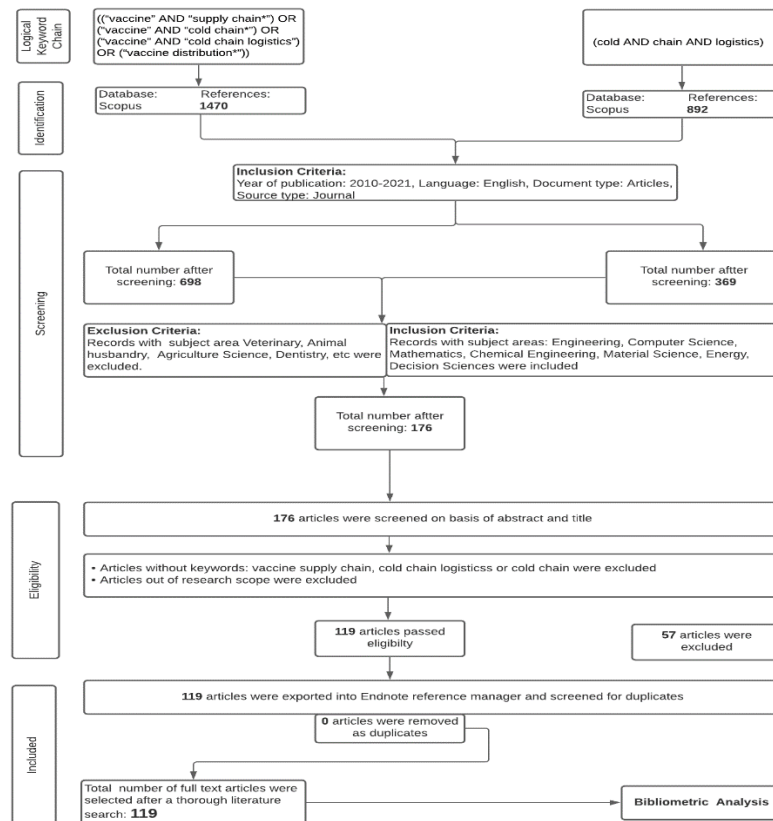


Fig. 1. Data collection procedures.

3 Results of the Bibliometric Analysis

The bibliometric analysis was conducted using a professional software called VOSviewer, and four primary classification analysis were performed, including: (1)

journal co-citation analysis; (2) keyword co-occurrence analysis; (3) analysis of the collaborations between countries and regions; and (4) document co-citation analysis. These analyses help to identify the publication trends, the most popular journals in this field, and the key areas that receive the most attention.

The annual and cumulative publications in vaccine supply chain and cold chain logistics are given in Fig. 2. As shown, there has not been a steady growth in the number of articles published each year. In 2014, a peak of 11 articles was published, which is followed by a decrease for the next three years. From 2018 to 2020, an increasing trend is observed with a total of 66 articles published, representing 55% of the total publications in the last decade. This result has shown that increasing focuses have been given to the vaccine supply chain and cold chain logistics, especially during the last three years.

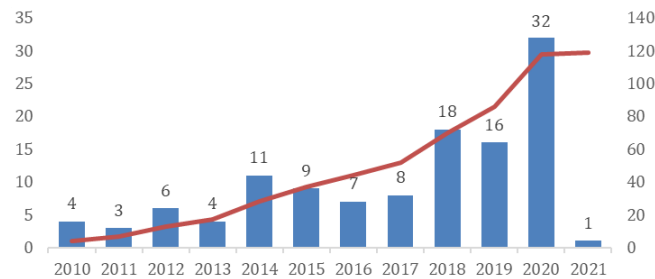


Fig. 2. Publication trends in vaccine supply chain and cold chain logistics.

3.1 Journal Allocation and Co-citation Analysis

The 119 papers selected in this research were published in 91 different journals. Table 1 shows the top 15 journals with more than two papers. These 15 journals have published 40 papers, which account for 34% of the total. As can be seen, *Computers & Industrial Engineering* has the highest number of publications in this field.

Table 1 Summary of the top 15 journals with the highest number of publications

Journal	Documents
Computers and Industrial Engineering	6
European Journal of Operational Research	4
Annals of Operations Research	3
Omega (United Kingdom)	3
Biologicals	3
Mathematical Problems in Engineering	3
Manufacturing and Service Operations Management	2
International Journal of Multimedia and Ubiquitous Engineering	2
International Journal of Information Management	2
Building and Environment	2
Journal of Biotechnology	2
Neural Computing and Applications	2
International Journal of Refrigeration	2
International Transactions in Operational Research	2
Open Cybernetics and Systemics Journal	2

A journal co-citation analysis was then performed to identify the most influential and co-cited journals in the vaccine supply chain and cold chain logistics literature. A network of 12 elements with 66 links was created from journals with more than 20 citations. The network shows two clusters of interlinked journals (Fig. 3). Cluster 1 consists of 5 journals, mainly in the field of operations research (OR), where *European Journal of Operational Research* has the most citations and the highest total link strength. Cluster 2 consists of 7 journals representing several research areas of OR and Management Science (MS), where *Management Science* is the most influential journal with a total link strength of 1449. Although OR and MS are often used interchangeably, the journals in Cluster 1 put more focuses on the development of mathematical models and computational algorithms. The journals in Cluster 2, on the other hand, focus on both methodological development and its applications and managerial implications. In addition, it is also observed that *European Journal of Operational Research* and *Management Science* are the most frequently co-cited journals in this field.

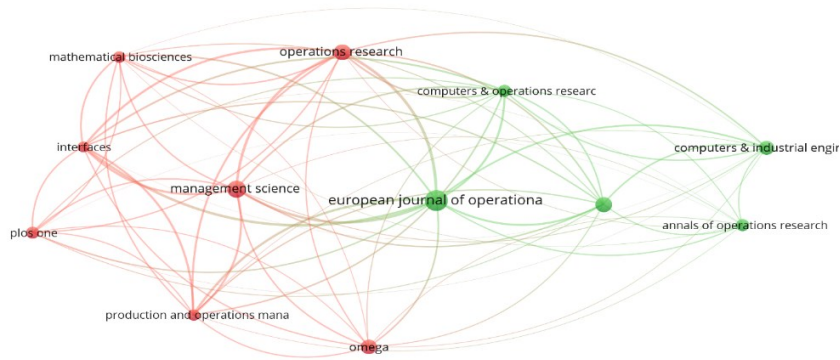


Fig. 3. Journal co-citation analysis.

3.2 Collaboration analysis between countries and regions

To identify the countries and regions actively involved in the study of vaccine supply chain and cold chain logistics, a co-authorship network of collaborating countries is created in Fig. 4. The minimum number of documents was set to 2, with each country having a minimum citation of 2. This yielded a total of 14 interconnected countries actively collaborating in this research area. As shown, China and the United States are not only the most important countries in this field but also have the most extensive collaborations. Table 2 presents the list of the countries and their contributions to vaccine supply chain and cold chain logistics. The average citation was calculated by dividing the number of citations of each country by the number of documents.

From the list, vaccine supply chain and cold chain logistics are popular research topics in the regions of Europe, North America, and Asia, where China has the highest number of published documents, followed by the United States. Although China has more publications than the United States, the United States has twice as many citations as China, which implies their publications may have a more substantial influence at the time of this study. In the table, the average year column represents the average year in

which the documents are published. It means that when comparing China and the United States, the latter has more documents published from 2015 as opposed to 2017 in the case of China. This may explain the reason why the publications from the United States have received more citations than the ones from China, because earlier publications have more influence in a research area and usually receive more cumulative citations.



Fig. 4. Mapping of collaborating countries.

Table 2 The countries and regions with the highest number of publications

Country or Region	Documents	Citations	Citations per document	Average year
China	47	182	3.87	2017
United States	36	385	10.69	2015
India	9	36	4.00	2018
Canada	5	17	3.40	2017
South Korea	4	41	10.25	2016
United Kingdom	4	48	12.00	2018
Australia	3	29	9.67	2016
Hong Kong (China)	3	15	5.00	2018
Spain	3	15	5.00	2014
Switzerland	3	26	8.67	2017
France	2	14	7.00	2013
Italy	2	76	38.00	2013
Saudi Arabia	2	19	9.50	2019
South Africa	2	15	7.50	2018

Furthermore, it is noteworthy that several countries, e.g., South Korea, the United Kingdom, Australia, Switzerland, and Italy have a few publications, but the average citations per document are extremely high compared to that of the papers from the other countries. This indicates their strong influences in this research field.

3.3 Co-occurrence Analysis of the Frequent Keywords

The keyword co-occurrence analysis is an assessment to show the main theme and focuses of a particular field. In this analysis, the minimum number of the keyword co-occurrences was set to 3. This criterion leads to 67 qualified ones out of the total 1407 keywords in all publications, which form 7 clusters with their co-occurrence relations. The top 10 keywords in vaccine supply chain and cold chain logistics with the highest

The document co-citation analysis is performed to identify the most influential documents in vaccine supply chain and cold chain logistics. The result from the co-citation analysis of the 119 selected papers is given in Fig. 6. It can be seen that Arifoğlu, Deo and Irvani [7], which studied the influenza vaccine supply chain with a focus on demand and supply, is the most influential document that has the highest number of citations and the strongest interplays in the co-citation map.

4 Discussions and Future Research Opportunities

The results of the bibliometric analysis reveal that the research topics on vaccine supply chain and cold chain logistics have received increasing attention during the last decade across different fields. Extensive studies have been done to support the decision making and to address the planning challenges at strategical, tactical, and operational levels over the four stages of a vaccine supply chain including product, production, allocation, and distribution [8].

4.1 Methods for vaccine supply chain and cold chain logistics

To solve the supply chain and logistical challenges, the methods from OR and MS have been extensively focused and widely adopted, and the most popular methods include optimization, simulation, and combined optimization-simulation.

Optimization is a prescriptive analytics that helps to find the optimal solution through using a model and/or an algorithm under several pre-determined rules and conditions. Optimization models and methods can be used to determine the system configuration of a vaccine supply chain and to make operational decisions related to the vaccine storage, allocation, and transportation of a cold chain distribution network. As logistics costs are directly proportional to customer responsiveness, the network design for vaccine distribution should be modeled to achieve low operating costs, while simultaneously, be capable of rapidly distributing vaccines to end-users, especially during the COVID-19 pandemic. In this regard, several studies have been conducted to determine the strategic location and allocation decisions, and the tactical relocation decisions. Mixed integer linear program (MILP) is the most widely used modeling technique in vaccine supply chain network design, which minimizes the total costs associated with the facility location and demand allocation through optimal decision making. Besides, multi-objective optimization has also been widely used to incorporate with other objectives of vaccine supply chain network design, e.g., carbon emission, customer satisfaction. At the operational level, the research focuses are given to the development of improved heuristics and meta-heuristics for the vehicle routing problems (VRP) and the inventory allocation problems in vaccine distribution systems.

Simulation is a descriptive analytics that helps to test several what-if scenarios and to evaluate the system performance in a dynamic environment. Unlike optimization, simulation focuses primarily on performance measurement but not on decision making. At the country level, the vaccine supply chain consists of four main stages including sourcing, storage, distribution, and administration [9]. Implementing simulation methods, e.g., Monte Carlo simulation, discrete event simulation, and system dynamics, in

professional software, e.g., AnyLogic and AnyLogistix, can help to evaluate different decisions in these four stages of vaccine supply chains and cold chain logistics systems. For instance, Shittu, Harnly, Whitaker and Miller [10] addressed the problems related to vaccines storage facilities in Nigeria by applying a simulation model to analyze the effect of the fluctuations from the vaccine supplies and demands on the storage capacity requirements.

Simulation-optimization can use the strengths of both methods and has thus been increasingly focused [11]. On the one hand, simulation can provide inputs and the prediction of parameters under a highly uncertain environment of an epidemic outbreak [12]. On the other hand, the optimization results can be evaluated in a more realistic simulation environment [13]. In this regard, Dillon and Colton [14] used a simulation-optimization method to determine the most economical design of vaccine warehouses in developing countries, and their study showed that this method could yield a more accurate result.

4.2 Future research opportunities

Even though increasing efforts have been spent during the last decade, there are still several research opportunities to tackle the challenges of vaccine supply chains and cold chain logistics during the COVID-19 pandemic. The following suggestions are made to guide future research:

1. The combination of advanced predictive analytics with optimization models is a promising direction for future study. The recent development of machine learning, deep learning as well as other artificial intelligence (AI) methods may improve the inputs and the effectiveness of the optimization models. Thus, more studies are needed in this field.
2. The combination of optimization and simulation needs to be enhanced to ensure the viability of a global vaccine supply chain under the pandemic.
3. The implementation of new technologies, e.g., drones, may improve the distribution and last-mile delivery of vaccines, so new models are needed to plan the cold chain logistics system considering the use of new technologies.
4. The mass vaccination will lead to a significant increase in the generation of infectious medical waste, so the reverse logistics issues associated with the mass vaccination should be focused on.

5 Conclusions

This paper presents a bibliometric analysis of 119 documents contributed to vaccine supply chain and cold chain logistics within the past decade. Using a network analysis tool, four classification analyses, namely, journal co-citation analysis, co-occurrence analysis of keywords, country collaboration analysis, document co-citation analysis, were made to understand the research landscape and the most popular methods. The results indicate that there has been a tremendous increase in the number of publications from 2018 with *Computers & Industrial Engineering* having the most publications. Besides, optimization and simulation have been widely used to support different decisions.

However, to tackle the unprecedented logistical challenges for the vaccine supply chain during the COVID-19 pandemic, future research needs to focus on methodological integration, incorporation with new technologies, and reverse logistics.

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