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Carbon Emission in Supply Chain: A Comprehensive Bibliometric Analysis

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Carbon emission (CE) has emerged as a prominent research area because environment emerged as a global concern all over the globe. With this sustainable supply chain model also grown rapidly based on social, economic and environmental parameter after conference of parties 16 (COP 16) in 2015. This sharp increase in research and fragmented findings and scattered scholarly contribution make it difficult to find how to explore the systematic development of the filed. This study presents a systematic bibliometric analysis of CE in Supply Chain (SC) by using Scopus database. A total 1000 most cited publication were selected those who are published between 2015 to 2025 for four different keywords: SC, CE, CE in SC and Sustainable Supply Chain (SSC). Scopus dataset and analysis were studied deeply then Bibliometric techniques were employed using VOS viewer software to analysis public trends, authorship network, keyword occurrence, institution support and country wise research contribution. In addition, a detailed manual analysis of 20 most cited articles in the subject domain on Mathematics was conducted to identify research themes, methodological approaches and emerging research directions. These findings highlight the evolution of research in this domain, identify the most influential authors, institutions and countries and reveal key thematic clusters shaping the field. Furthermore, the study provides insight into the most effective research methods used in carbon emission studies within supply chains and highlight potential areas for future investigation. This bibliometric review contributes to a better understanding of the intellectual of the field and demonstrate the importance of bibliometric review in enhancing research productivity and guiding scholars toward promising research in the field of SSC.

Keywords: Sustainable Supply Chain Management, carbon emission, Green supply chain, Greenhouse gas emission, machine learning

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Third industrial revolution (1960-2000) was a big transformation from analogue to digital transformation. As a result of this CE has emerged as a critical global challenge due to global manufacturing and supply chain (SC). T. Wiedmann and J. Minx explain CE is the total amount of climate relevant greenhouse gas emission (GGE), from industries, logistic operations and transportation. This drawn significant consideration due to impact of this, global warming creates ecological emplacement. SC include procurement, production, transportation and distribution of end products, are the main contributors in CE. Therefore, inclusion of sustainability in SC models provides strategic advancement like risk mitigation, price competitiveness, brand reputation etc. illustrated by J. Sun, et.al. Sustainable supply chain management (SSCM) include social and environmental aspects into traditional SC practices discussed by S. Seuring and M. Muller. SSCM ensure operational efficiency and economic viability of production and minimize negative environmental impact introduced by T. Feng, et.al. Although growing number of research on SSC is a good sign of increasing global concern towards SC but disperse research domain creates a chaos in the field of research. With multidisciplinary contribution in sustainable SC there is a need for systematic mapping of existing research, identification of prominent research theme, influential work and research gaps. Bibliometric analysis proposed a systematic approach to evaluate all the parameter such as co-authorship, citation networks, origin of research, keywords, development and dynamics of a research field by using software. This search used VOS viewer because of its open-source nature and capacity of handling large amount of data with highest journal coverage and easy to present text data as discussed in U. Bukar et.al. This can enable systematic data processing, network analysis, which makes easy to find future scope in the research domain. This study presents a comprehensive analysis of CE in existing SC models aiming to overview of research progress from all indexed research paper in Scopus database. This review answers the following questions:

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1. Which Researcher's, institution's, countries, contribute significantly in CE?

2. What is the important research theme for future research in this field?

3. What are the existing research trends on CE in SSCM?

This paper is structured in the following sections. Section 1 describes the research methodology adopted in the study; Section 2 presents the findings of bibliometrics analysis and Section 3 concludes the main insights of research paper.

RESEARCH METHODOLOGY

This study includes systematic bibliometric techniques to systematically study of CE and their integration with SSCM. The data used for this study is from 2015 to 2025 from Scopus database because of rapid increase in research. Bibliometric analysis is important for this as it provides transparent, analytical and quantitative evaluation of a large number of research publication. For data collection Scopus database was used because of its large number of databases, with high quality articles, peer reviewed journals, citation indexing and global acceptance of listed journals. Scopus database includes interdisciplinary domains like; SC, CE and SSCM. This search includes English language research papers, review papers, conference proceedings to ensure academic consistency. The time duration from 2015 to 2025 is taken for previous evolution and recent developments in the field which make easier to find gaps for the future scope in the research domain.

A structured keyword search method was used in a two-step keyword searched framework. The first one used CE related keyword and in the second one captured sustainable SC related keyword (like; SSC, green supply chain). Boolean operator and/or to include more research article related to search. The final search query was applied for titles, abstract and other keywords to ensure and relevance check according to research domain. In addition, perform keyword co-occurrence to find the conceptual linkage of research domain with finding literature. After data extraction conduct a multi-level screening and refinement process to remove delicacy in records, followed by exclusion of irrelevant articles, duplicate records were removed. After this perform a content alignment check and then we got a final dataset suitable for bibliometric analysis which ensure relevancy and quality of the analysis. To avoid fragmentation author names, institutions and country names were standardize and keywords with similar meaning (e.g. green supply chain and SSC) were merged to improve accuracy of SC and interpretability of bibliometric result.

The total findings of this analysis were theoretically interpreted under the domain of SSC management with linkage of CE and sustainability. This analysis highlights CE effects SC and decision related to SC. Also identifies the research gap and future scope of research based on findings and underexplored research area. Particular attention is findings of new methods instead of traditional one, inclusiveness with current SC, beneficial as per industrialization 4.0, and inclusion of quantitative models for accurate results.

RESULTS AND DISCUSSION

To ensure a comprehensive bibliometric review of the CE in supply chain this search was conducted using the "Article Title, Abstract and Keywords" fields to search the most relevant articles related to the topic. Initially a broad search was conducted by using the keywords Supply Chain (SC) and CE which gives us 213546 and 350267 publications from the period 2000 to 2025. This shows scholarly attention towards CE was historical. In addition, a second search was conducted using the keywords Sustainable Supply Chain (SSC) and Carbon emission in SC resulting 33861 and 7685 research publications for the same time period 2000 to 2025, which reflect a rapid growth of sustainability in supply chain in last 25 years. The significant global policy shift in climate change globally observed after COP21 Paris agreement held in 2015, so that this research study restricts the time window from 2015 to 2025 for two main reasons:

I. To study about intensified academic focus on carbon emission, research trends, modelling approaches towards SC, CE and SSC.

II. To reduce the dataset of papers for detailed bibliometric analysis.

Accordingly for the refined search Supply Chain (SC) and CE keywords use for the time period 2015 to 2025, total 150447 and 260831 publications were found, similarly same search conducted for the keywords SSC and CE in SC for the same time period resulted 30005 and 6850 publications, which indicate a steep rise in research after COP21. In addition, to explore the inclusion of mathematical models in CE and Green Supply chain (GSC) we perform a search with keywords CE Mathematical model in supply chain resulted 375 publications for the same period, which shows lots of future scope in the field of SC and GSC by the help of mathematical approaches might be performed in the upcoming years and combine multidisciplinary research can be conducted for the future research for novelty and inclusion of other fields (like use of technology, software, AI, or mathematical model) in carbon emission.

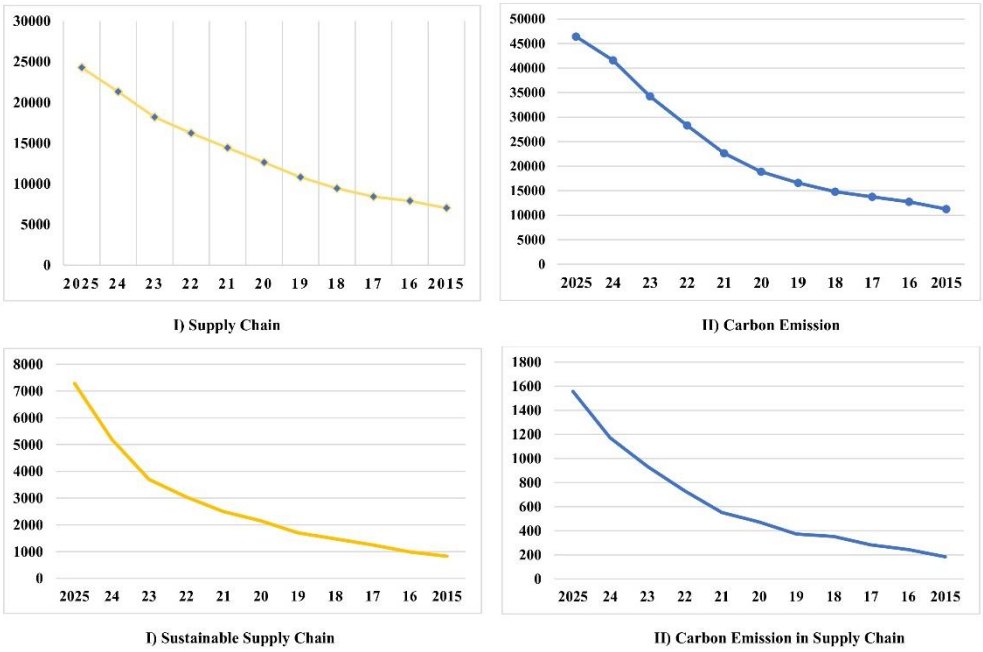

Figure 1. Year wise trends of publications.

Annually Research Publication Trends

The year wise distribution of publications for the keywords SC shows a rapid growth in last two decade. Publication activity shows an upward trend from 2010 with a notable increase after 2015, In 2015 total number of publication was only 7019 and after this this increase gradually and in 2025, 24103 total number of paper were published. This reflects highlighted academic and policy attention towards SC from global institution which will increase in upcoming years and India will play a major role in this area of research. For the domain CE publication trend is same and from 2015 to 2025 number of publications is continuously increasing and in 2025, 46288 total number of paper published. For the key words CE and same trends found for the keyword SSC with highest number of papers in 2025 which is 7203. In the last for the keyword SSC and last search for the keyword CE in SC resulting the same 1549 paper in a year 2015, distribution shown in the, **Figure 1** summarizes the yearly distribution of the publications.

Classification of Publication by Documents Category

A document type search conducted for the keywords SC, a large number of literatures composed of journal article with number 93689 out of 150447 then followed by conference paper, book chapter and review articles. For CE keywords journal article resulting highest number of papers in journal article with 197334 numbers and then conference paper, review articles and book chapter. In the case of SSC again journal article at the top with 17924 numbers followed by conference paper, book chapter, and review article. For the keywords SSC and keywords CE in SC dominance of journal article remains at the top with the article 5139 then followed by conference paper, review article, and book chapter, **Figure 2** reflects the segmentation of literature according to document type. This overall bibliometric study shows that research on CE area and SC dominated by research article and conference paper which may help to future researcher to focus study around them.

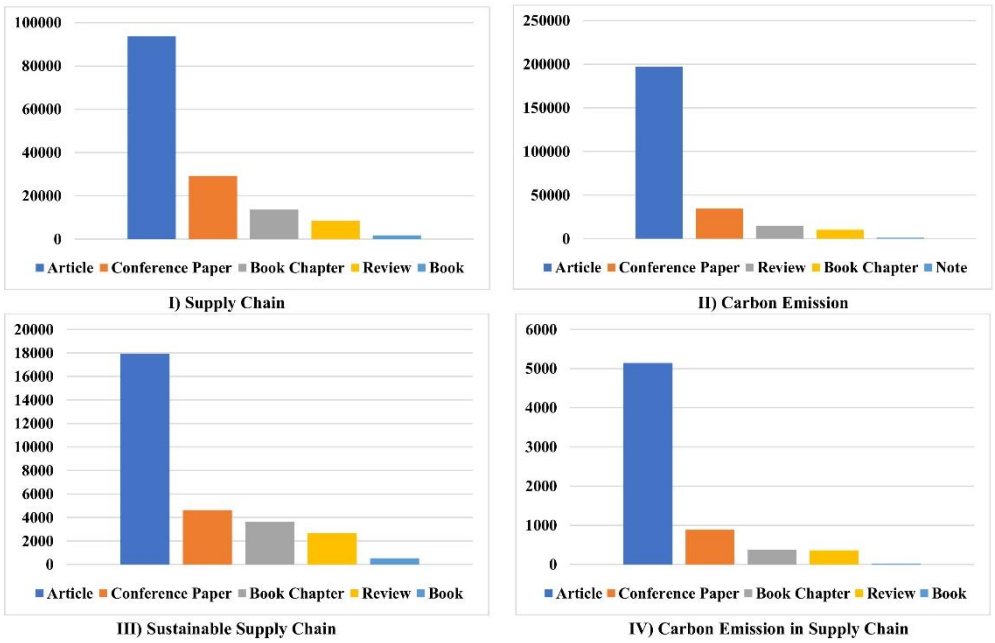

Figure 2. Document wise trends of publications.

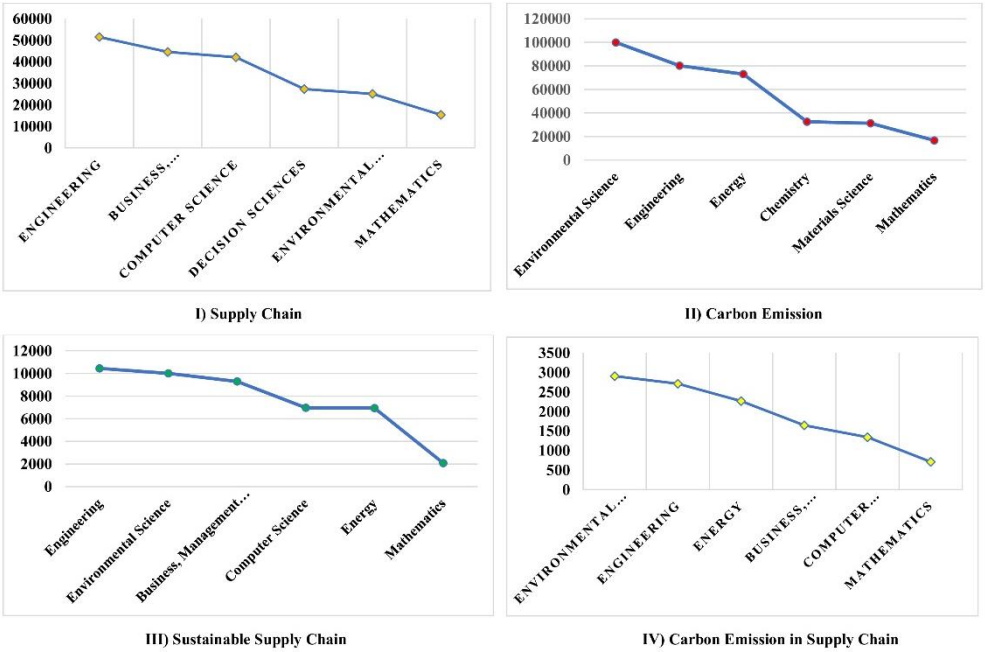

Figure 3. Subject type trends of publications.

Disciplinary Distribution of Research

An analysis for the subject area shows that on SC during the period of 2015 to 2025 dominated by engineering-oriented research with 51418 papers leads the area, Management and accounting comes second followed by environmental science, social science, energy economics and mathematics. The subject area related to CE is dominated by Environmental science with paper 99881 papers followed by Engineering, Energy, Chemistry, Material Science, Chemical Engineering and Mathematics. For the keywords SSC shows a balance integration of technical, environmental and mathematical domain.

Engineering contributes majorly with 10414 articles and then Environmental Science, Management and accounting, energy, economics etc. At the last for carbon emission in supply chain shows a strong collaboration between environment and engineering with highest publication 2903 in environmental science followed by Engineering, Energy, Business management and accounting, Social Sciences, mathematics and Economics, shown in the **Figure 3**. Across all four keyword Engineering consistently dominates and highlight the central role of technology driven approaches in supply chain, with this Mathematics does not comes in top three domain. The integration of modern engineering tools with mathematics models and simulation offers substantial scope for future research and this may present a promising direction for interdisciplinary and high impact research.

Global and Institutional Contribution Analysis

The affiliation and country wise analysis for key words SC shows a focus on leading institution and country contributing in SC domain. This analysis shows that Ministry of Education of People's Republic of China is the leading organization in this domain followed by The Hong Kong Polytechnic University and the Chinese Academy of Sciences, this shows that China's focused contribution in SC area with 29882 publications. In this research area USA is in second place followed by India (16793 Publications), European Countries then by UK and Germany. The same search conducted for keywords CE shows again largely contribution based on China (90254 Publication), which originates mainly from Chinese Academy of Sciences followed by Ministry of Education of People's Republic of China, Tsinghua University and Peking University. China leads the global research output in this domain followed by USA, India (24252 Publication), UK, Germany. For the keyword SSC leading affiliations are from University of Tehran, Wageningen University and Research and Ministry of Education of People's Republic of China, with this India Graphic Era Deemed to be university is in top 10 position in article publication. China emerges again top contributor (4658 Publication) in this domain but India is in the second place (4342 Publication), shows growing research contribution with leading economic growth driven by environmental sustainability followed by USA, UK, and Italy. Analysis for the keyword CE in SC resulting The Chinese Academy of Sciences is in the top followed by Tsinghua University and Ministry of Education of People's Republic of China, Illustrated in the **Figure 4**. China is in the top followed by USA, India (725 Publications) and UK. This analysis shows that India is growing research contributor in the domain related to CE and SC, which provide a large scope of future research in this domain, **Figure 5** shows the country wise distribution.

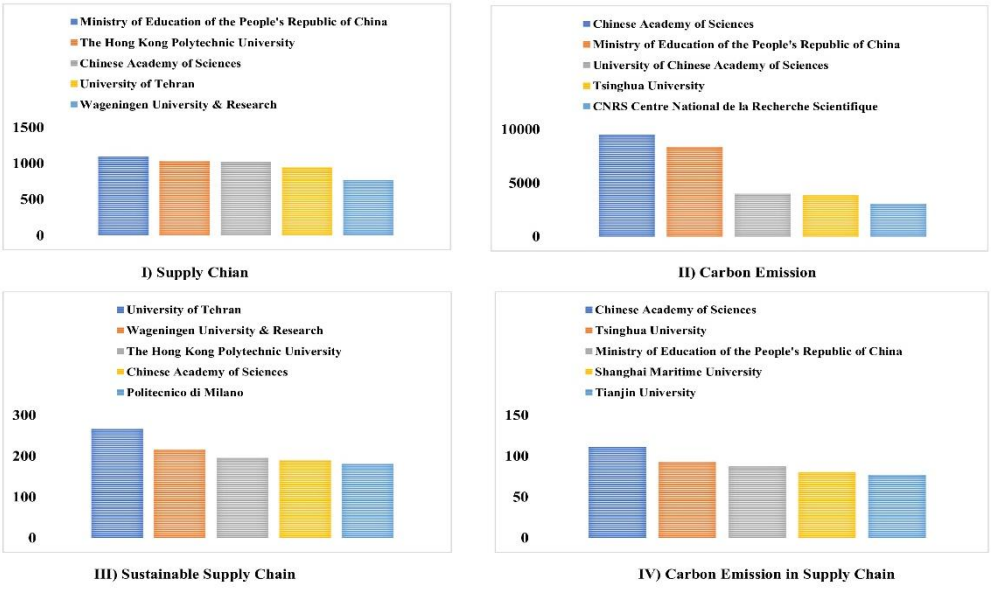

Figure 4. Institutional contribution trends of publications.

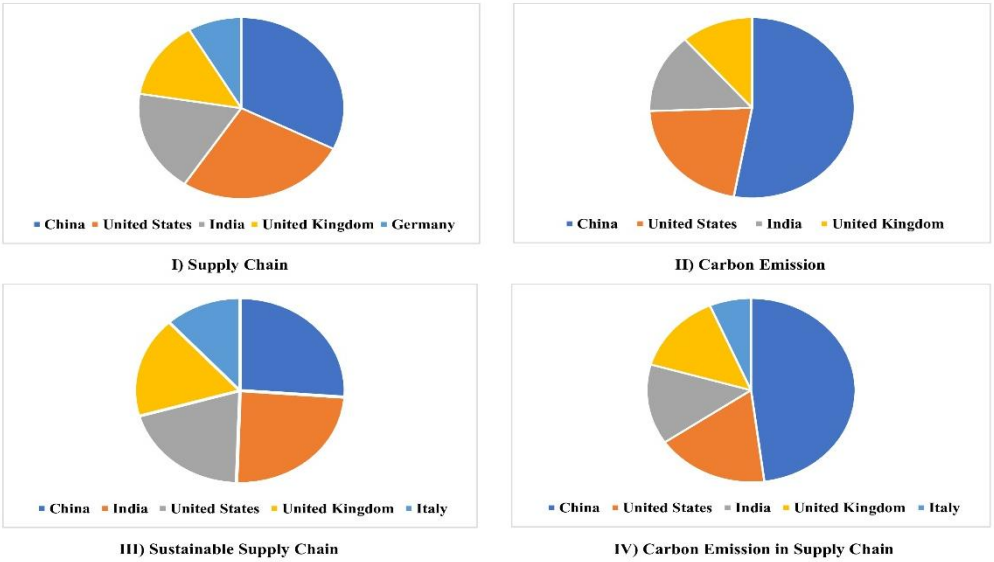

Figure 5. Country wise trends of publications.

Journal Productivity Analysis

The journal wise analysis was performed to study the backbone of research that what kind of journal are publishing papers in sustainability. In this methodology we conduct a search for the keyword SC, CE, SSC, and CE in SC found that journal of cleaner production is the top publisher in the domain of CE and CE in SC with publication 6541 and 514. For the domain SC and SSC Sustainability Switzerland is in the top with article 3748 and 1871. International journal of production Economics, International journal of production research, Energies and etc. journal also have a prominent role in this sustainability domain, **Figure 6** provide an overview of the journals.

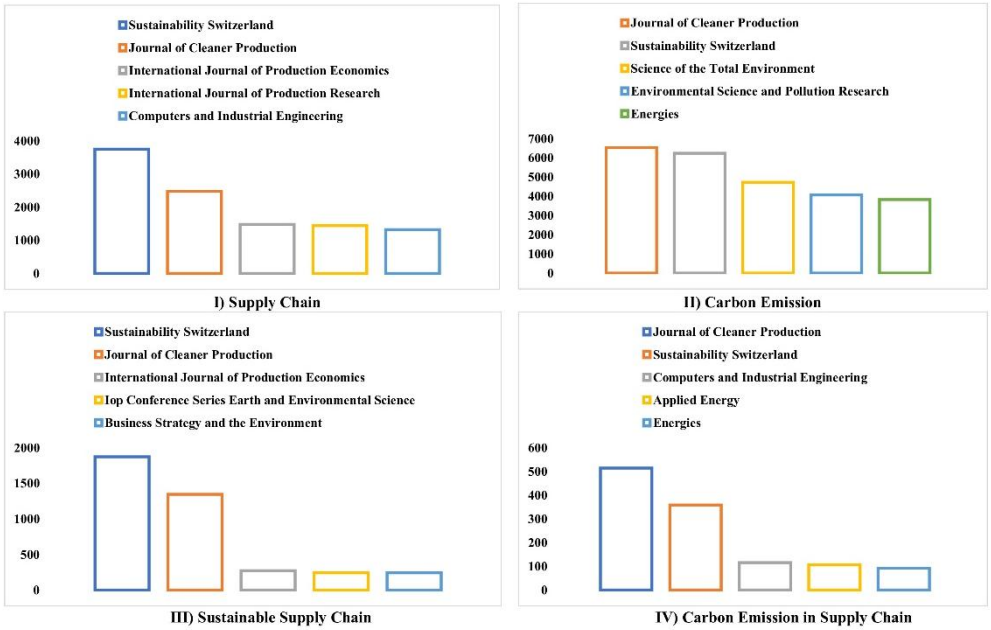

Figure 6. Journal productivity trends of publications.

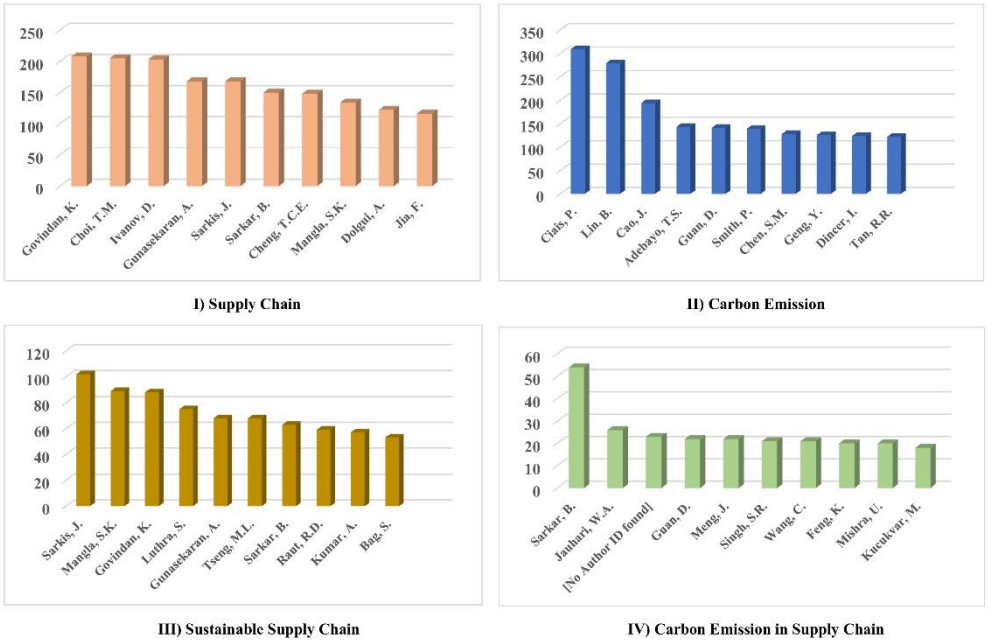

Figure 7. Author's productivity trends of publications.

Author Productivity Analysis

This analysis shows an interconnected among the four keywords i.e. SC, CE, SSC, CE in SC. In the SC domain main contributors are Govindan (208), followed by Ivanov and Choi shows strong dominance and well-established research field characterized by Operations Management (OM). In contrast CE keyword is led by Ciais (309) and Lin reflecting maximum publication in the field of Environmental science energy and climate modelling instead of OM. When analysis conducted for SSC, resulting Sarkis (102), Mangla and Govindan are the top scholars and advice environmental sustainability within SC research for the emerging domain of CE in SC, Sarkar (54) and Jauhari, Gaun are the main contributor foe the domain. Above research shows that Sarkis and Govindan appear consistently across multiple clusters, indicates their pivotal role in bridging traditional SC with modern sustainability which shifts from operational efficiency to decarbonization and environmental accountability with global SC network, shown in **Figure 7**.

VOS Viewer Analysis

This study used bibliometric approach to examine the intellectual and collaborative structure of the research on SC. Data were collected from Scopus dataset using the keywords "SC" for the period 2015 to 2025, dataset was restricted to the top 1000 most cited papers and analyzed by using VOS viewer (version 1.6.x) to visualize co- authorship network. The option creates a network based on bibliometric data and three levels of analysis were conducted separately, first one is author wise, then organization level and last Country level co-authorship. Network visualization maps (Figure 8) were generated to study clusters, link strength and collaboration patterns. Node size shows publication and citation impact, while link thickness indicates the higher collaborative relationship. The author level network in shows that dense collaborative patterns characterized by cohesive research clusters, this structure indicates high impact SC research is largely reflects diversification across sustainability, resilience, healthcare supply chain and risk management. At the organizational level leading universities and research centers are from China, North America and Europe are at the top and shows strong inter institutional linkages and interdisciplinary integration between SCM, health care sectors, and food industry. The Country level network indicate a globally interconnected system where China emerging as a highly contributor followed by the USA and India. China shows a regional contribution in Asia and USA serves as a global hub linking Europe, Asia, and leading economies in the word. European union, Indonesia, Turkey shows strong regional interaction.

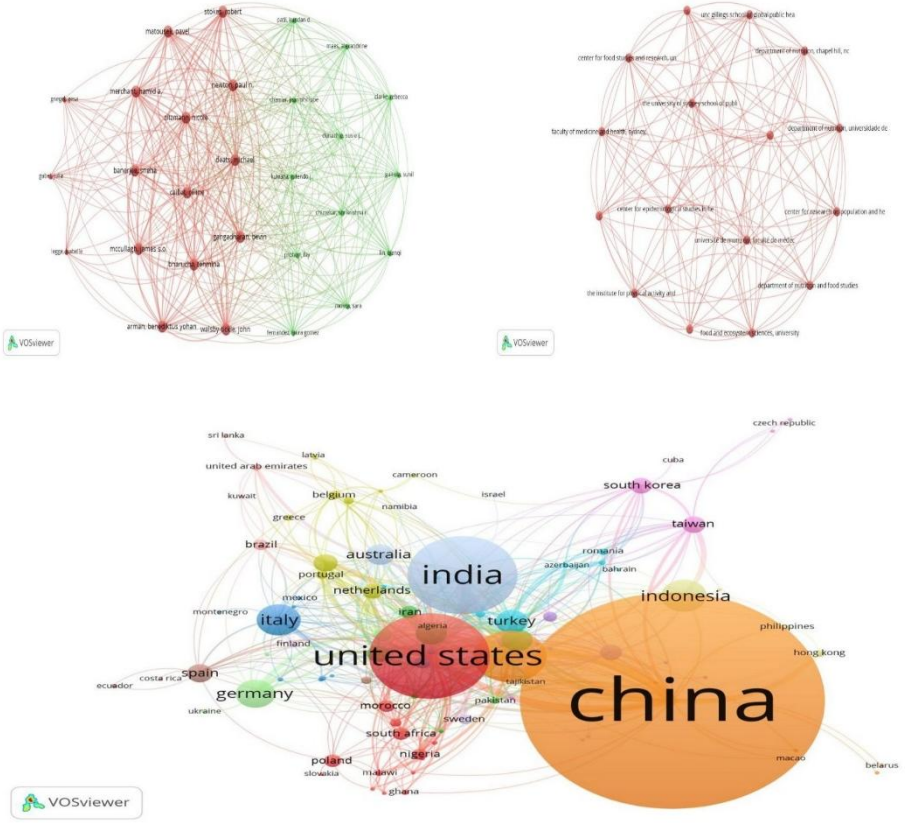

Figure 8. Network map by VOS viewer for SC.

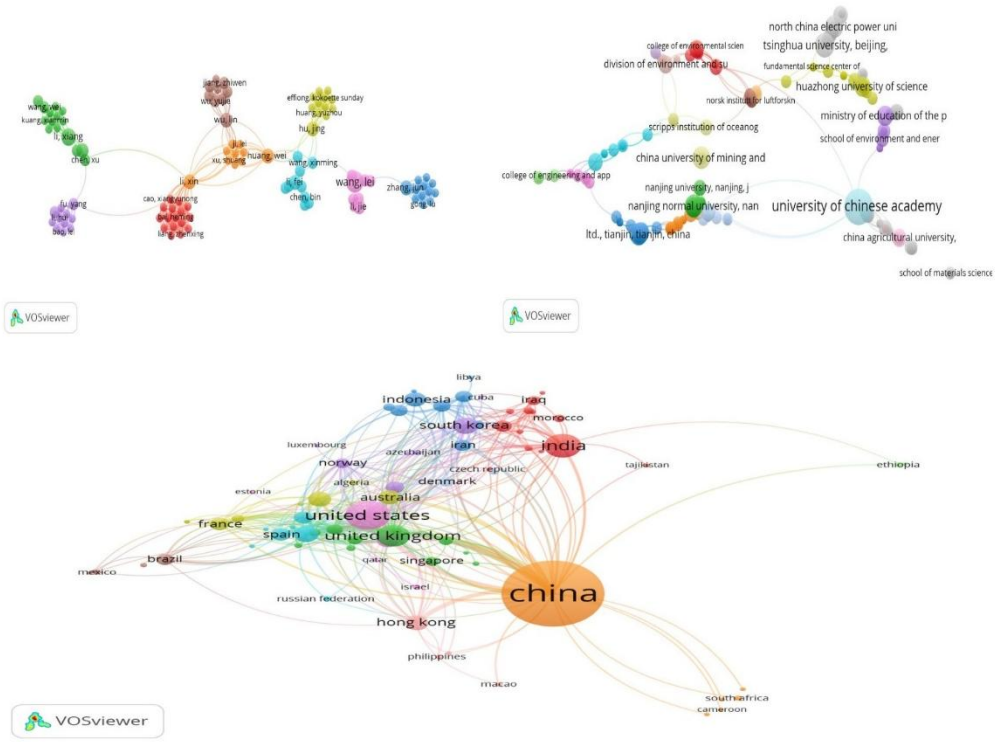

Figure 9. Network map by VOS viewer for CE.

A bibliometric co-authorship analysis for the keyword carbon emission was conducted for most 1000 cited research article for the same time period. The network map shows that prominent authors such as Li Xin, Huang Wei, Wu Lin and Hu Jing occupy strong position. The visualization suggests that research based on CE during this period is largely dominated by Asia and particularly by Chinese scholars reflecting regional policy priorities related to carbon neutrality and environmental sustainability followed by USA and India. The organizational co authorship network represent The University of Chinese Academy of Science Academy of Science appears at the top followed by Tsinghua University, Huazhong University of Science and Technology and Nanjing Normal University also form the strong nodes within the network. Overall, this mapping reveals that institutional collaboration plays a crucial role in advancing research on carbon emission where India is also in the leading contributor in this domain illustrated in Figure 9.

A rigorous bibliometric analysis for the keyword SSC conducted and this network analysis (Figure 10) shows that the country level collaboration network shows that a highly interconnected global search where China emerge as a strong contributor which indicate longest node links with USA, India, UK and Australia. The USA is showing highest linkage with European union and other part of the globe. India forms an important collaboration cluster with countries such as Iran, Iraq etc. which reflect India collaborations with growing economies in carbon emission research area. At the organizational level the co-authorship network shows that leading universities from China like University of Chinese Academy of Sciences, Huazhong University of Science and Technology, China University of mining and Technology shows their important contribution to high impact research. The university of Chinese academy of science emerge as an important institution hub with strong collaborative links to multiple universities and research organization. Overall, this network demonstrates that CE research is highly concentrated among leading universities and also shows inter universities collaborations.

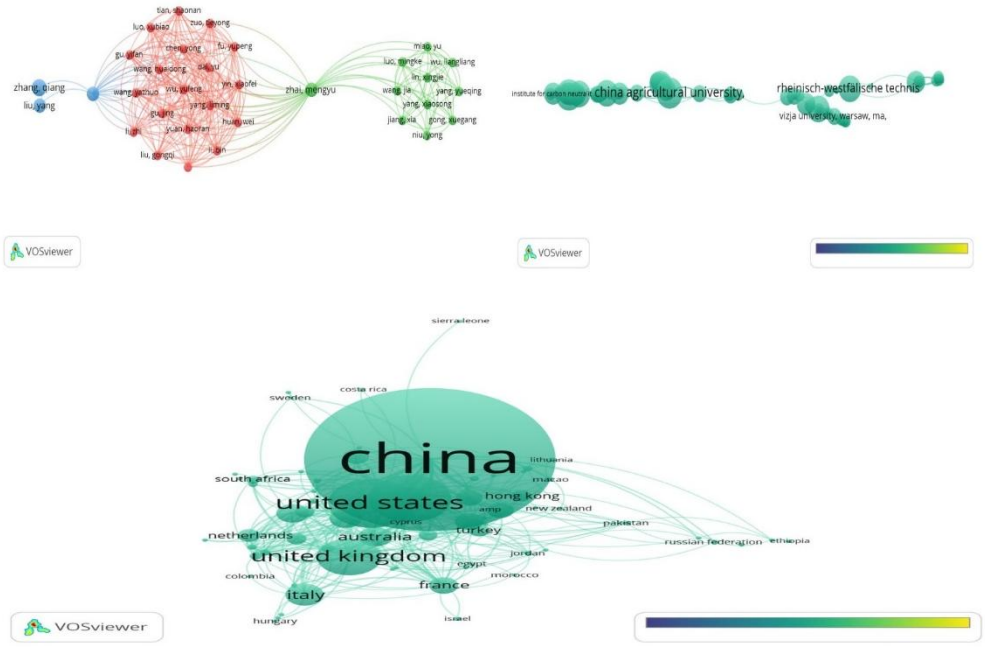

Figure 10. Network map by VOS viewer for CE in SC.

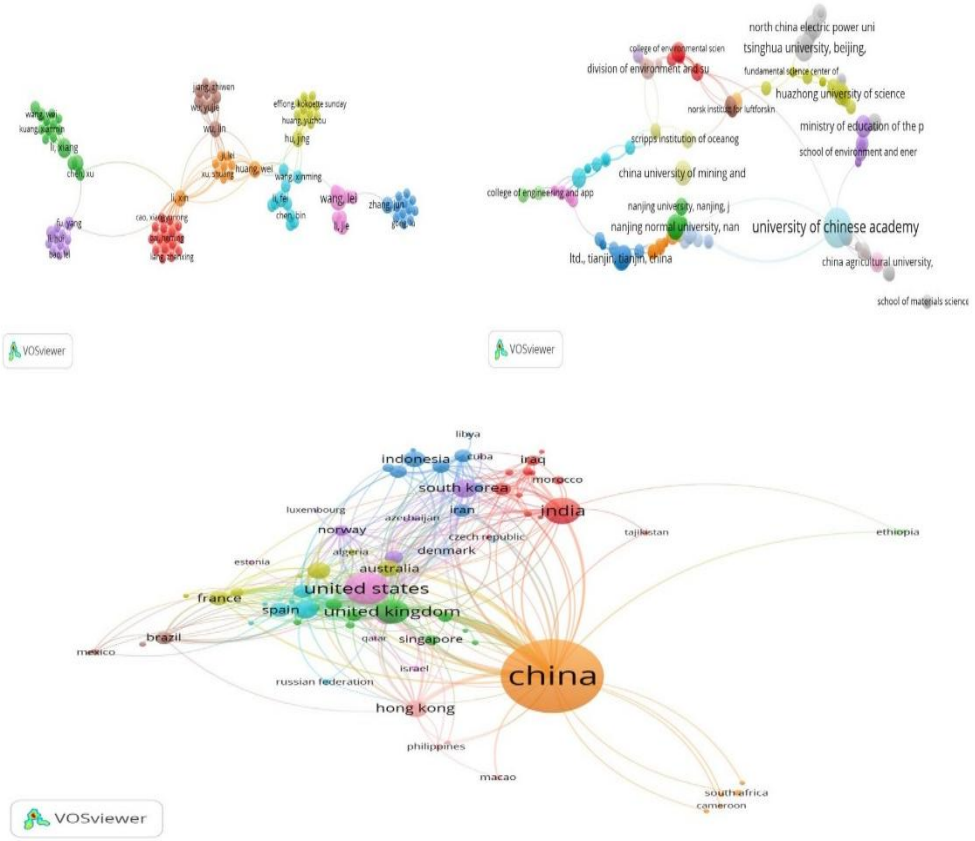

Figure 11. Network map by VOS viewer for SSC.

This bibliometric co-authorship analysis for was conducted to search the collaborative structure of the domain CE in SC for the same period. The author level map shows a strong collaboration among the authors, and research groups. A major cluster includes Chen Yong, Dai Yu, Wang Huaidong and Yang Liming shows strong collaboration, Zhai Mengyu connects multiple research group and Zhang Qiang and Liu Yang shows an emerging collaboration group. The organization level collaboration network shows Chinese institution dominance, institution like University of Chinese academy of sciences, Tsinghua University, Huazhong University of Science and Technology, Nanjing Normal University are the important institution in the field of the domain. This research also shows strong collaboration among the Germany and Poland institution shows cross national institution partnership. At the country level the visualization shows a highly connected network dominated by Chinese scholars and institutions followed by United states and then by UK. China collaborates with Australia, France, Italy, Turkey etc. shows the main role in the field of CE in SC. USA links Europe, Africa, Asia shows an important collaboration hub among the continents shown in Figure 11. Overall, the Co-authorship network for the author, organization and countries indicate a strong collaborative intensity, important role of Chinese institution and scholars and a growing role of developing economies in the field of CE.

Analytical and Mathematical Perspective in Top Cited Article

To ensure the analytical regularity and mathematical innovations, this search employed four key searches i.e. SC, CE, SSC, CE in SC for the same duration 2015 to 2025, while restrict the subject area exclusively to Mathematics. This subject wise filtering was applied to study formal modelling, optimization and analytical solution which approaches to carbon related SC problems. This mathematical oriented search yielding 15388 documents for SC, 16718 documents for CE, 2076 research articles for SSC and 712 publications for CE in SC. For the future research top 20 most cited papers were selected to examine mathematical models used, key findings of the research and future research scope also discussed to reduce CE and improve efficiency of the models. This approach enables a deeper understanding of how mathematical modelling help in reducing carbon emission and develop SSC.

Table 1: Supply Chain Publications

Author's	Citations	Mathematical model/ Analytical model	Key findings	Future scope
Govindan, et.al. (2015)	1681	Network flow model	Identify key structures and drivers of CLSP	Integration of advance tool like AI
Sharma, et.al. (2020)	668	Predictive and classification models	How ML improve forecasting and sustainability performance	Use of hybrid ML optimization models
Govindan, et.al. (2017)	606	Stochastic and robust optimization	Address uncertainty in SC design	Multi stage real uncertainty modelling can use
Zhu, et.al. (2017)	600	Game theory (Nash equilibrium)	Green design can improve profit under competition	Adoption of multi-player and dynamic games
Qin, et.al. (2017)	585	MCDM, Interval type-2 fuzzy sets	This improves decision accuracy under uncertainty	Application of hybrid fuzzy optimization frameworks
Friha, et.al. (2021)	522	Network and data driven models	IOT enhances visibility and efficiency	Mathematical modeling based IOT can be used
Sacks, et.al. (2020)	520	Simulation and cyber physical modelling	Digital twins improve supply chain coordination	Use of optimization driven digital twin
Attaran, et.al. (2023)	503	Simulation and system dynamics	Identified value creation through digital twins	Apply mathematical validation of twin accuracy
Nguyen, et.al. (2018)	459	Statical and optimization models	BDA enhances SC agility and performance	Integration of prescriptive analytics integration
Zhang, et.al. (2015)	455	Game theoretic coordination modelling	How awareness impacts pricing and emissions	Behavioral and dynamic demand area may explore
Banaeian, et.al. (2018)	427	Fuzy TOPSIS	This can improve supplier sustainability ranking	Use of large-scale fuzzy optimization
Shahjalal, et.al. (2022)	422	Life cycle and optimization models	This highlighted reuse potential in SC's	Integration of closed loop battery supply chain models
Fahimnia, et.al. (2015)	421	Stochastic and risk models	Shows risk integration improve resilience	Integrated risk sustainability models
Nikolopoulos, et.al. (2021)	416	Time series and growth models	During COVID, lockdown create a severe SC disruption	May use pandemic resilient SC models
Rajendran, et.al. (2015)	411	Logic and cryptographic models	This improved security in digital SC system	This secure information networks
Akundi, et.al. (2022)	395	Human centric system models	This shows shift towards human AI collaboration	Mathematics- AI collaboration can be used
Venkatesh, et.al. (2020)	386	Block chain and graph models	This improved transparency and traceability	Application of blockchain enabled SC's
An, S. et.al. (2021)	382	Stackelberg game models	This shows green financing reduces emissions	Carbon linked financial optimization can used
Brandon, et.al. (2017)	380	Energy system optimization model	Hydrogen is the key to low-carbon emission	Application of integrated hydrogen supply chain models
Zhang, et.al. (2020)	376	Game theoretic pricing models	Sharing of information impacts profits	Multi-channel coordination models can be used

Table 2: Carbon Emission Publications

Author's	Citations	Mathematical model/ Analytical model	Key findings	Future scope
Hoesly, et al. (2018)	1415	Time series emission accounting models	This provides consistent long term global emission dataset	Coupling with real time climate economic models can reduce emission
Meinshause, et al. (2020)	1189	Integrated assessment and concentration pathway models	Extended SSP's for long term climate projections	Uncertainty quantification in extreme scenarios can reduce greenhouse gas
Shan, et al. (2020)	962	Input output and inventory models	Improved accuracy of China's accuracy	Application of dynamic regional emission modeling
Chen, et al. (2020)	763	Spatial data analysis	Revealed regional emission disparities	Integration of multi scale spatial optimization
Hurtt, et al. (2020)	763	Integrated land use transition models	Standardized land use data for climate models	Coupling land use and carbon optimization

Werner, S. (2017)	661	Energy balance and optimization models	District system can reduce CE	Can do smart optimization of urban energy networks
Zhang, et al. (2019)	638	Thermodynamical conversion models	Biochar effective for carbon sequestration	Life cycle optimization may be used in biochar SC
Pata, et al. (2021)	623	Augmented ARDL with structural breaks	Validated Environmental Kuznets curve (EKC) under renewable integration	Nonlinear and panel EKC models
Papadis, et al. (2020)	619	Energy system optimization models	Identified barriers to deep decarbonization	Application of multi objective energy optimization
Jeswani, et.al. (2020)	611	Life Cycle assessment (LCA) based emission models	This shows biofuels are not always carbon neutral	This can use hybrid LCA economic optimization
Tang, et al. (2015)	594	Cointegration and casualty models	Growth and Foreign Direct investment increase emissions	Integration of dynamic panel emission modeling
Brown, et al. (2018)	551	Linear optimization and network flow	Sector computing used	Stochastic renewable optimization technique can optimize energy system
Solarin, et al. (2017)	545	Autoregressive distributed lag (ARDL) and causality models	Evidence supporting pollution haven	Use of panel econometric models improve results
Aziz, et al. (2021)	539	Thermodynamic and cost optimization models	Hydrogen viable for low carbon energy	Adoption of hydrogen SC optimization
Hanif, et al. (2019)	538	Panel cointegration models	Use of fossil fuel raises emissions	Can use green finance and policy modelling
Dong, et al. (2017)	488	Panel regression and causality models	This shows renewable process can reduce emissions	Nonlinear energy transition models use improve the results
Shahbaz, et al. (2020)	487	Econometric modeling	Renewable energy can promote growth	Growth emission decoupling models can use
Liu, et al. (2016)	464	Aerosol microphysics models	Aerosol can improve climate interaction	Application of high-resolution aerosol optimization
Aguiar, et al.	437	Computable General Equilibrium (CGE) models	Standard global trade emission data	Dynamic CGE climate coupling can apply
Van Marle, et al. (2017)	429	Fire emission and proxy models	Long term fire can estimate emissions	Coupling fire models with land optimization

Table 3: CE in SC Publications

Author's	Citations	Mathematical model/ Analytical model	Key findings	Future scope
An, et al. (2021)	383	Game theoretic supply chain financing model under carbon cap	Green credit financing is more effective than trade credit in reducing carbon emission when carbon limits are tight, financing choice affects pricing and emission decision	Extended to multi echelon supply chains, include stochastic demand and dynamic carbon prices
Allaoui, et al. (2018)	254	Two-stage hybrid MCDM	Integrating sustainability objectives improves agro-food supply chain design and tradeoffs between cost, environmental and social criteria	Real time data integration, uncertainty and resilience considerations
Soysal, et al. (2018)	253	Green inventory routing optimization model	Horizontal collaboration significantly reduces emissions and logistics costs for perishable products	Behavioral aspects of collaboration and digital coordination platforms can include

Yang, et al.	250	Remanufacturing of supply chain model under cap and trade	Optimal collection models depend on carbon price and quota; cap and trade promote remanufacturing	Hybrid carbon policies can change consumer return behavior
Abbasi and Ahmadi (2023)	222	Systematic literature review	Carbon policies strongly influence network design decision	Can include empirical validation of social sustainability
Wang, et al. (2021)	190	Game theoretic coordination model with altruistic preference	Altruism can improve both emission reduction and supply chain profit under proper coordination	Heterogeneous behavioral give preference to experimental validation
Hussain, et al. (2023)	174	Energy economy analytical framework	Green transition may worsen energy poverty without policy support	Policy design linking SC, energy access and quality
Quin, et al. (2021)	151	Long term energy system optimization model	Carbon neutrality pathways require structural changes in energy SC	Regional SC impacts uncertainty in technology adoption
Cao, et al. (2020)	148	Dual channel supply chain pricing model under carbon tax and subsidy	Carbon tax and remanufacturing subsidy jointly influence pricing and channel	Consumer carbon awareness can integrate
Alegoz, et al. (2021)	132	Comparative analytical model, manufacturing and hybrid system	Hybrid manufacturing and remanufacturing system outperform the pure system under carbon tax	Use of multi product and multi period extension
Kaur and Singh (2018)	129	Big data driven optimization model	Big data analytics can improve sustainable procurement and logistics efficiency	AI based decision support and real time carbon tracking can apply
Ren, et al. (2022)	127	LCA models	Emissions vary significantly across vehicle types and usages scenarios	Integration with supply chain routing and policy incentives
Stanelyte, et al. (2022)	126	Review and analytical classification	Demand response service can support low carbon energy supply chain	Quantitative integration with logistic and manufacturing
Xu, et al. (2018)	123	Contract based analytical supply chain model	Price discount contracts can coordinate dual channel supply chains under emission constraints	Application of Blockchain enabled contracts
Fu, et al. (2023)	116	Game theoretic production and technology choice model	Green technology investments under carbon tax	Dynamic technology learning can improve policy competition
Acquaye, et al. (2018)	113	Quantitative sustainability performance measurement model	Integrated metrices better capture environmental performance of supply chain	Integration of standardization of carbon metrices
He, et al. (2021)	101	Consumer sensitive analytical supply chain model	Carbon sensitive consumer significantly affects pricing and delivery decisions	Empirical demand estimation can integrate
Lou and Ma (2018)	97	Two parallel supply chain analytical model	Trade off exists between sales effort and emission reduction efforts	Use of Incentive compatible coordination mechanisms
Chen, et al. (2017)	97	Particle swarm optimization for closed loop SC	Metaheuristic methods efficiently solve complex low carbon CLSC problems	Hybrid algorithms and large-scale industrial applications
Wang, et al. (2019)	91	Joint replenishment and carbon trading optimization model	Carbon trading can influence replenishment frequency and cost emission balance	Volatile carbon markets and multi firm trading dynamics can integrate

Table 4: Sustainable Supply Chain Publications

Author's	Citations	Mathematical model/ Analytical model	Key findings	Future scope
Sharma, et al. (2020)	668	Machine learning (ML) based predictive and classification models	ML can enhance efficiency, sustainability and resilience	Hybrid ML optimization and real time decision models can use
Qin, et al. (2017)	585	Interval type 2 fuzzy Interactive and Multicriteria Decision Making (TODIM)	This improves supplier ranking under uncertainty	Integration with large scale optimization
Friha, et al. (2021)	522	Internet of Things (IOT) network and data analytics models	IOT can improve traceability and efficiency	Can develop Mathematical modeling of IOT enabled SSC's
Banaeian, et al. (2018)	427	Fuzzy TOPSIS/Group decision models	Selection of effective sustainability based on supplier selection	Application of real time fuzzy models
Akundi, et al. (2022)	395	Human centric system models	Shift towards human AI collaboration	Can develop Mathematical human loop optimization
Venkatesh, et al. (2020)	386	Blockchain and graph theoretic models	Blockchain can improve transparency and trust in SC	Optimization based blockchain model for SSC's integration
An, s.et al. (2021)	382	Stackelberg game models	Results green finance can reduce emissions	Models of carbon linked financial optimization models
Barbosa-Povoa, et al. (2018)	368	Optimization and network design models	Identification of key challenges in SSC	Multi objective SSC models can be develop
Azadi, et al. (2015)	355	Fuzzy Data Envelopment Analysis (DEA)	Evaluation can improve efficiency	Machine Learning (ML) based Hybrid DEA models can apply
Zakeri, et al. (2022)	310	Energy system optimization	Crises can accelerate energy transition	Development of crisis resilient SC models
Stojčić, et al. (2019)	299	Multi Criteria Decision Making (MCDM)	MCDM widely used for sustainability	Modern technology based MCDM models can be installed
Allaoui, et al. (2018)	254	Two stage multi objective MCDM optimization	Sustainability oriented supplier selection	Develop large scale stochastic agriculture-based SC models can develop
Reimann, et al. (2019)	253	Closed Loop SC (CLSC) models	Process innovation can boost remanufacturing	Integration of dynamic CLSC models
Biswas, et al. (2023)	251	Game theoretic and traceability models	Tradeoff between transparency and cost	Integration of sustainability and traceability models
Yang, et al. (2021)	230	Competitive pricing and subsidy models	Subsidies can promote green innovation	Models based on dynamic policy driven
Abbasi, et al. (2023)	221	Carbon constrained network models	Carbon policy can shape SC design	Integrated policy network optimization can be use
Rouyendegh, et al. (2020)	219	Intuitionistic fuzzy TOPSIS	This shows fuzzy TOPSIS improved decision accuracy	Hybrid fuzzy DEA ML models can improve the results
Ghadimi, et al. (2018)	217	Agent based optimization	Use of decentralized sustainable decision can be use	AI driven adaptive agent system can apply
Govindan, et al. (2015)	213	Robust bi- objective stochastic models	Shows tradeoff between cost and sustainability	Adoption of advanced hybrid metaheuristics
Hjorth, et al. (2022)	205	Human robot interaction models	Use of robotics supports circular economy	Integration of human robot in SSC's

RESULTS AND DISCUSSION

This bibliometric analysis reveals an important expansion of scholarly research on CE within the SC domain for the time duration 2015-2025. The result demonstrates that global research output increases sharply after COP21 Paris Agreement which heighted the growing academic policy in sustainability and SC. The analysis indicates that journal articles dominate the literature across all keywords categories, suggesting that the field is primarily driven by peer reviewed research contribution. Country wise analysis reveals that China leads the global research output in SC and carbon related studies which is followed by USA and India shows increasing role of developing economies in sustainability research. Institutional analysis further confirms the dominance of Chinese research organization such as Chinese Academy of Sciences and Tsinghua University, which act as major research hubs in the CE domain. Author productivity analysis highlights influential scholars such as Govindan, Sarkis and Ivanov who play a key role in integrating traditional SSCM with sustainability and environmental considerations. The VOS viewer network map analysis also demonstrates strong collaborations relationship at author; institutional and country levels show the interdisciplinary and globally interconnected nature of CE research. Therefore, the subject specific analysis in mathematics reveals growing interest in optimization models, analytical frameworks and computational approaches reducing CE and improve SC efficiency. These findings suggest that involving sustainability science, environmental policy and mathematical modelling.

The analysis illustrates several themes that can guide future studies in the field of CE within SSCM. One of the most significant directions is the development of advanced mathematical models using advance tools like software and technology, future research can also focus on integration of emerging digital technology like AI, Big data analytics, Internet of thigs (IOT) to reduce carbon emission in SC. Another way to explore is development of circular and green supply chain frameworks, carbon policy mechanism with multidisciplinary approach that help scholars to reduce CE in SC.

Existing research on CE in SSCM shows an important direction in recent literature. Many studies focus on carbon footprint measurement and emission assessment across the supply chain which quantify greenhouse gas emission generating during production, transportation, shortage and distribution activities. Researchers continuously emphasize optimization and simulation models to reduce emission, a strong trend towards integrating industry 4.0 technology big data, IOT, blockchain enable real timing, monitoring, transparency and trackability of carbon emission. This literature also highlights low carbon logistic and green supply chain strategies, including energy efficient transportation and sustainable production process. This study indicates that CE in SSCM is evolving technology driven, data based analysis and multidisciplinary approaches aimed at reducing environmental impact while developing SSC, Mathematical formulation and models can make this more accurate and appropriate for the upcoming SC.

CONCLUSION

This depth analysis of the 1000 reviewed papers shows that the most extensively used research model is the multi objective optimization model, top 20 most cited papers in all four keywords shows that multi objective linear programming and mixed integer programming is widely used by the previous scholars. The dominance of this model is primarily due to balancing capability of its conflicting objectives, such as minimizing total supply chain cost while reducing carbon emissions. Researcher prefer this approach because sustainability problem is inherently trade off driven, mathematically traceable, easier to solve by using the standard solver and adaptable in different supply chain configuration. Despite all this several loopholes are evident because most multi objective models depends on static assumptions such as fixed demand, constant emission factors and stable energy prices. Out of 100 publications many studies ignore behavioral, policy driven, technological disruption and limited research in end-to-end supply chain integration and another major gap is lack of validation and dynamic modelling.

This research identifies several effective ways to reduce carbon emissions in supply chain i.e. green logistics optimization, energy efficient production and renewable energy adoption, sustainable supplier selection and collaboration, circular economy practices and digital technologies and data driven monitoring. To achieve optimal solutions, researchers mostly use robust mathematical and analytical models. The most effective model use by researcher is multi objective linear programming for balancing cost and trade-offs, mixed integer nonlinear programming (MINLP) to solve complex network design problems. Goal programming is used to satisfy environmental and economic models simultaneously and fuzzy logic-based decision models to handle ambiguity in sustainability. The overall conclusion of this research should focus on integrating this above technique into dynamic and data driven models to develop practical carbon reduction models in SSCM.

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