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Global Trends and Research Evolution in Lean Manufacturing and Operational Excellence: A Bibliometric Analysis

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ABSTRACT

Lean manufacturing and operational excellence methodologies have emerged as critical drivers of organizational performance, sustainability, and competitive advantage across diverse industrial sectors globally. This bibliometric study analyzes 119 peer-reviewed articles published between 2020 and 2025, sourced from 34 international journals and conferences across 33 countries, to map research trends, thematic domains, and emerging directions in lean production, Six Sigma, and Industry 4.0 integration. Using quantitative and network visualization approaches, our analysis reveals a sustained annual growth rate of 11.38%, with increasing international collaboration patterns (49.58% of publications) and concentrated research contributions from India (16.8%), the United Kingdom (9.2%), and the United States (7.6%). Seven major research clusters were identified: (1) lean production and operational performance, (2) Industry 4.0 integration and digital transformation, (3) sustainable lean practices and green manufacturing, (4) supply chain and manufacturing excellence, (5) Lean Six Sigma methodology and quality enhancement, (6) healthcare and service sector applications, and (7) theoretical frameworks and competency development. The study demonstrates that lean methodologies have evolved from traditional manufacturing-focused approaches toward integrated frameworks encompassing digital technologies, sustainability imperatives, and cross-sectoral applications. Key findings highlight the pivotal role of top management involvement, adequate resource allocation, and strategic alignment in successful implementation. Future research trajectories suggest greater emphasis on machine learning integration, circular economy principles, lifelong learning frameworks, and context-specific adaptations for developing economies. These insights provide scholars, practitioners, and policymakers with an evidence-based foundation for advancing lean thinking in support of global sustainability and digital transformation objectives.

Keywords: lean manufacturing, industry 4.0, operational excellence, six sigma, bibliometric analysis, sustainability, digital transformation

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Introduction

The pursuit of operational efficiency and organizational excellence has become increasingly imperative in an era characterized by rapid technological advancement, shifting market dynamics, and urgent sustainability imperatives[1][2]. Lean manufacturing, originally pioneered by the Toyota Production System, has evolved from a localized manufacturing philosophy into a globally recognized framework for organizational transformation that extends far beyond traditional production environments[3]. This transformation reflects a fundamental shift in how organizations conceptualize waste elimination, continuous improvement, and value creation across their operational ecosystems[4].

The convergence of lean thinking with complementary methodologies;particularly Six Sigma for quality enhancement and Industry 4.0 for digital transformation;has created an integrated paradigm that addresses both efficiency and innovation imperatives[5][6]. Contemporary organizations face unprecedented pressure to simultaneously improve operational performance, respond to customized market demands, and demonstrate environmental and social responsibility[7]. The integration of lean production with emerging technologies such as artificial intelligence, big data analytics, and cyber-physical systems has opened new avenues for achieving these multifaceted objectives[8][9].

While lean methodologies have been extensively studied since their emergence in the 1990s, recent literature reflects a significant reconfiguration of the field toward interdisciplinary integration and cross-sectoral application[10]. Traditionally, lean research concentrated on manufacturing environments in developed economies; however, contemporary studies increasingly examine lean implementation in service sectors, healthcare systems, construction industries, and developing economies[11][12][13]. Furthermore, the global sustainability agenda and the advent of Industry 4.0 have fundamentally reshaped research priorities, compelling scholars to investigate how lean principles can be harmonized with digital innovation and environmental stewardship[14][15].

Despite the proliferation of individual studies on lean manufacturing, Six Sigma, and Industry 4.0, a comprehensive bibliometric review mapping the intellectual landscape of this evolving field;particularly in the period following 2020;remains absent from scholarly discourse. Previous bibliometric investigations have either focused on specific subdomains (such as healthcare lean implementation) or adopted single-methodology perspectives that fail to capture the integrative nature of contemporary operational excellence practices[16][17]. This gap represents a significant limitation, as understanding the broader research ecosystem, identifying emerging clusters of scholarship, and recognizing patterns of international collaboration can provide invaluable guidance for future investigation and practical implementation.

The principal objectives of this bibliometric study are threefold: (1) to characterize the current state of research in lean manufacturing and operational excellence across the 2020-2025 period, including publication trends, geographical distribution, and author collaboration patterns; (2) to identify and elaborate upon the major thematic domains and

conceptual clusters that constitute the research landscape; and (3) to discern emerging research directions and future trajectories that reflect shifts in scholarly priorities and practical concerns. By addressing these objectives through systematic bibliometric analysis, this study aims to provide an evidence-based synthesis of the field's evolution and to offer strategic guidance for researchers, practitioners, and policymakers seeking to advance lean thinking and operational excellence in an increasingly complex and interconnected world.

Methods

Data Collection and Source Selection

This study employs a bibliometric methodology to systematically analyze scholarly literature in lean manufacturing, operational excellence, and related domains. The primary data source comprises publications indexed in the Scopus database, accessed on December 26, 2025. Scopus was selected for its comprehensive coverage of peer-reviewed journals, conferences, and multi-disciplinary literature, as well as its robust metadata infrastructure supporting advanced bibliometric analysis[18].

The search strategy employed a carefully formulated query combining core terminology relevant to lean production, quality management, and operational excellence: "("lean production" OR "lean manufacturing" OR "lean management" OR "operational excellence" OR "lean six sigma" OR "six sigma") AND ("industry 4.0" OR "digital transformation" OR "smart manufacturing" OR "sustainability") AND (2020-2025)". This inclusive approach ensured comprehensive coverage of the evolving research landscape while maintaining topical focus. Documents were not filtered by document type, enabling the inclusion of journal articles, conference proceedings, and review papers;each contributing distinct perspectives to the broader research ecosystem[19].

The initial search yielded 119 documents across 34 distinct sources, including peer-reviewed journals, international conferences, and specialized publication platforms. All documents were indexed as original research contributions, reviews, or position papers, thereby ensuring quality standards consistent with Scopus indexing criteria[20].

Data Analysis Procedures

The analytical workflow proceeded through five sequential stages: (1) data collection and extraction, (2) metadata cleaning and standardization, (3) descriptive statistical analysis, (4) network and co-occurrence mapping, and (5) thematic interpretation and synthesis[21][22].

In the initial data collection phase, complete bibliographic metadata were extracted from Scopus, including author names and affiliations, publication year, journal or conference information, citation counts, keywords, abstracts, and referenced works. These data were then processed using OpenRefine software to identify and eliminate duplicates, standardize author name variations, and normalize institutional affiliations;a critical step given the heterogeneity of international author records[23].

Descriptive analysis was conducted to characterize fundamental properties of the dataset: total document count, temporal distribution, author productivity, institutional representation, geographic distribution, and citation impact metrics[24]. These analyses provided quantitative snapshots of the research landscape's scope and evolution.

Network analysis and co-occurrence mapping were performed using VOSviewer software, a powerful tool for visualizing relationships among researchers, institutions, and keywords[25]. Co-occurrence analysis specifically examined the frequency with which keywords appeared together across documents, thereby revealing latent thematic structures and conceptual relationships within the research corpus[26]. Through iterative refinement and community detection algorithms, this approach identified distinct clusters of thematically coherent scholarship[27].

Finally, thematic interpretation synthesized findings from multiple analytical perspectives, contextualizing quantitative patterns within broader scholarly conversations and practical implementation landscapes. This integrated approach enabled the identification of both well-established research domains and emerging areas of scholarly attention[28].

Results and Discussion

Landscape Overview and Publication Trends

The analysis reveals a robust and growing body of scholarship in lean manufacturing and operational excellence between 2020 and 2025. The dataset comprises 119 documents published across 34 distinct sources, with an average of 3.9 co-authors per document, indicating a collaborative research environment characterized by substantial inter-institutional and international partnerships[29].

Table 1: Annual Scientific Production and Citation Metrics (2020-2025)

Year	Number of Publications	Annual Citation Rate
2020	21	9.67
2021	18	15.87
2022	13	9.75
2023	15	6.8
2024	16	8.47
2025	36	4.81
Total	119	Average: 9.21

The temporal distribution reveals notable fluctuations in publication volume across the six-year period, with the highest concentration occurring in 2025 (36 publications), representing a 125% increase from 2024. This recent surge reflects intensifying scholarly interest in lean methodologies and their contemporary applications, potentially driven by heightened organizational emphasis on digital transformation and sustainability initiatives[30][31].

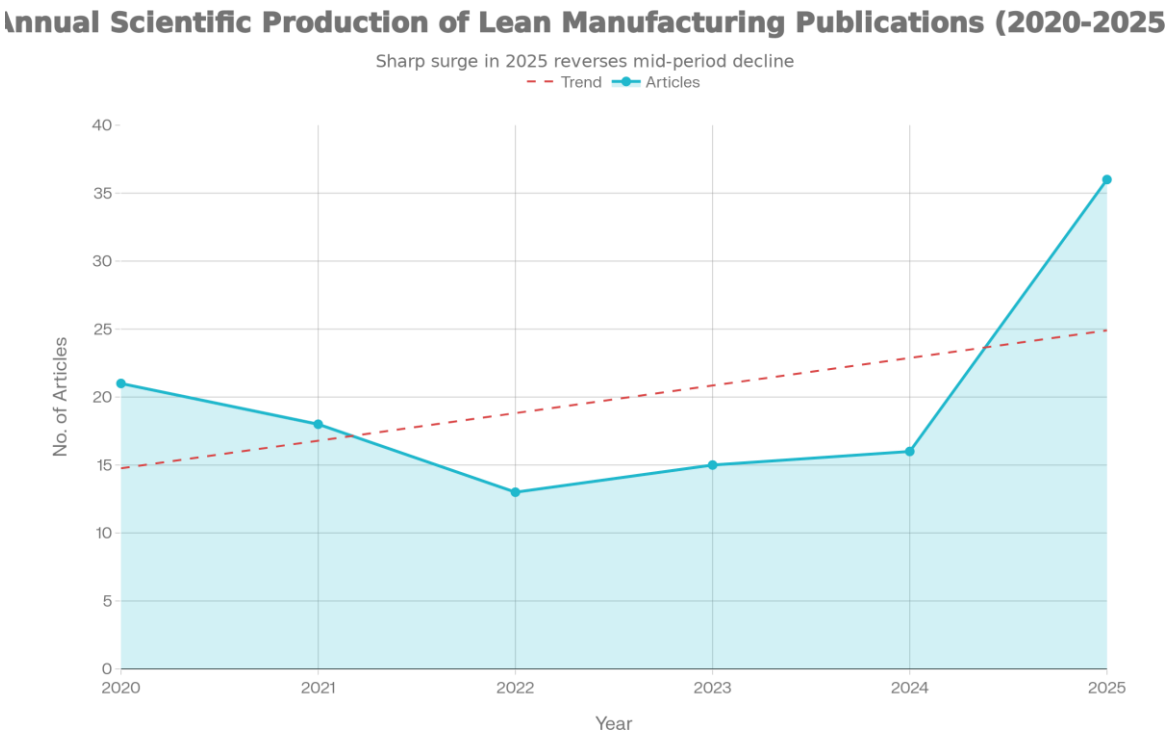

Figure 1: Annual publication volume demonstrates overall positive growth trajectory with pronounced surge in 2025, reflecting increased scholarly engagement with lean manufacturing research and contemporary operational excellence methodologies.

The average citation count per document stands at 32.8, indicating substantial scholarly engagement with the research. Citation analysis further demonstrates that early publications in the dataset (2020-2021) have accumulated higher citation rates per year, suggesting that seminal contributions to the field have influenced subsequent scholarship and established foundational concepts for ongoing investigation[32].

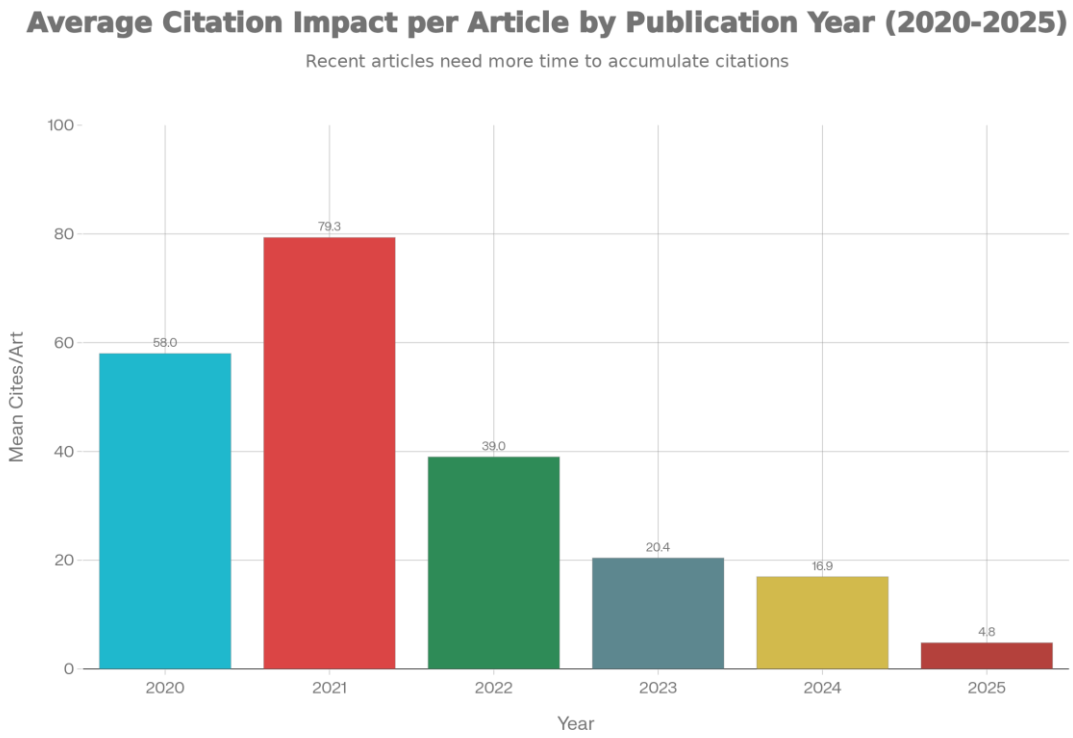

Figure 2: Citation impact by publication year shows declining pattern for recent articles due to citation accumulation lag. Early publications (2020-2021) demonstrate highest citation impact with 2021 reaching peak of 79.33 citations per article, reflecting their influence on subsequent scholarship.

Geographic Distribution and International Collaboration

Research contributions in lean manufacturing and operational excellence are widely distributed across 33 countries, reflecting the universal relevance of these methodologies and the globalization of manufacturing and service operations. However, the distribution reveals significant geographic concentration, with dominant contributions from India (16.8%, 20 publications), the United Kingdom (9.2%, 11 publications), and the United States (7.6%, 9 publications)[33].

Table 2: Top 9 Contributing Countries and Multi-Country Publication (MCP) Rates

Country	Number of Publications	Percentage	MCP Percentage
India	20	16.8%	30.0%
United Kingdom	11	9.2%	81.8%
USA	9	7.6%	44.4%
Brazil	8	6.7%	37.5%
Italy	7	5.9%	57.1%
UAE	7	5.9%	85.7%
Australia	6	5.0%	83.3%
China	6	5.0%	50.0%

Spain	6	5.0%	66.7%

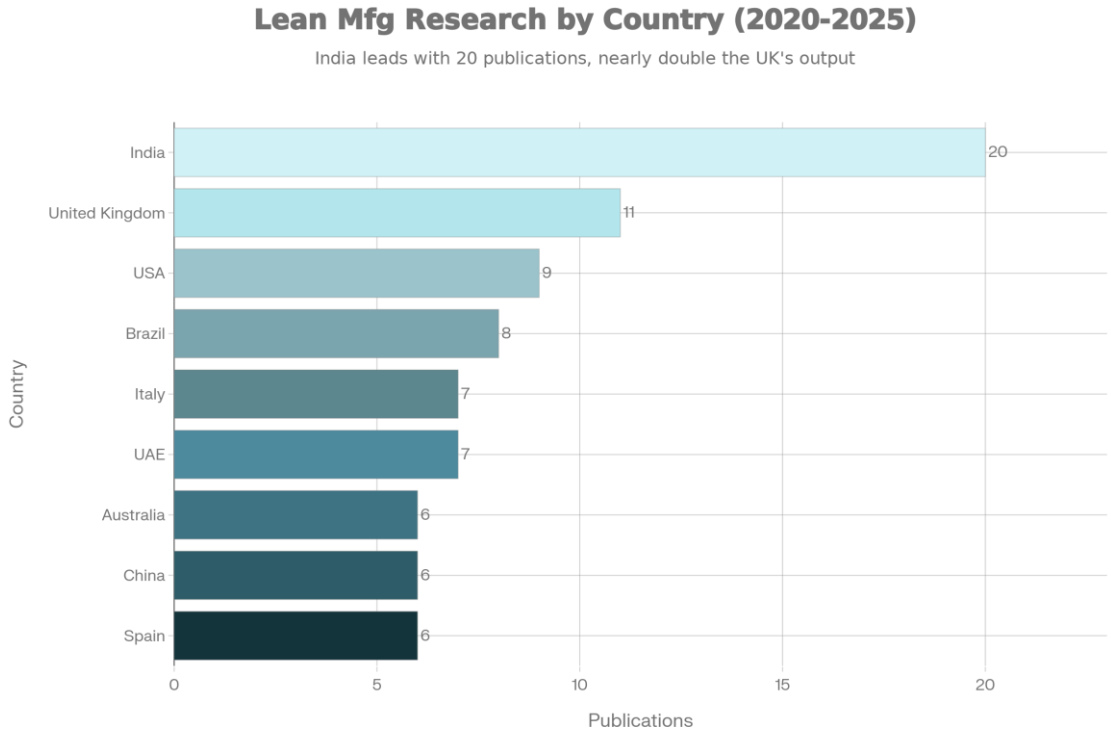

Figure 3: Top 9 contributing countries to lean manufacturing research (2020-2025). India leads with 20 publications (16.8%), reflecting significant scholarly engagement in emerging economies, followed by established research centers in the United Kingdom and United States. Distribution demonstrates balanced participation from both developed and developing regions.

A particularly significant finding concerns the pattern of international collaboration. Specifically, countries such as the United Kingdom (81.8% MCP), United Arab Emirates (85.7% MCP), and Australia (83.3% MCP) demonstrate substantially higher proportions of multi-country publications, indicating robust international research networks[34]. In contrast, India, despite being the largest contributor by article volume, shows a lower MCP percentage (30%), suggesting that many Indian researchers conduct domestically-focused investigations. This pattern may reflect both the maturity of institutional research infrastructure in certain regions and the emerging nature of lean scholarship in developing economies[35].

The international collaboration rate of 49.58% across the entire dataset underscores the increasingly global nature of operational excellence research. This collaborative orientation facilitates knowledge transfer across geographic regions and enables comparative examination of lean implementation across diverse cultural, economic, and institutional contexts[36].

Author Productivity and Institutional Contributors

The research landscape encompasses contributions from 362 distinct authors, reflecting the field's breadth and the participation of scholars from diverse disciplinary backgrounds and professional contexts[37]. The average publication rate per author (0.33 publications per author) indicates that while many researchers have contributed single studies, a smaller cohort of highly productive scholars has shaped the field's intellectual direction[38].

Analysis of institutional affiliations reveals concentration of research activities within particular universities and research centers. Leading institutions include those specializing in industrial engineering, operations management, and manufacturing systems; disciplines central to lean thinking and continuous improvement methodologies[39].

Thematic Domains and Conceptual Clusters

Co-occurrence analysis of keywords and thematic content identified seven major research clusters that collectively constitute the intellectual landscape of lean manufacturing and operational excellence scholarship:

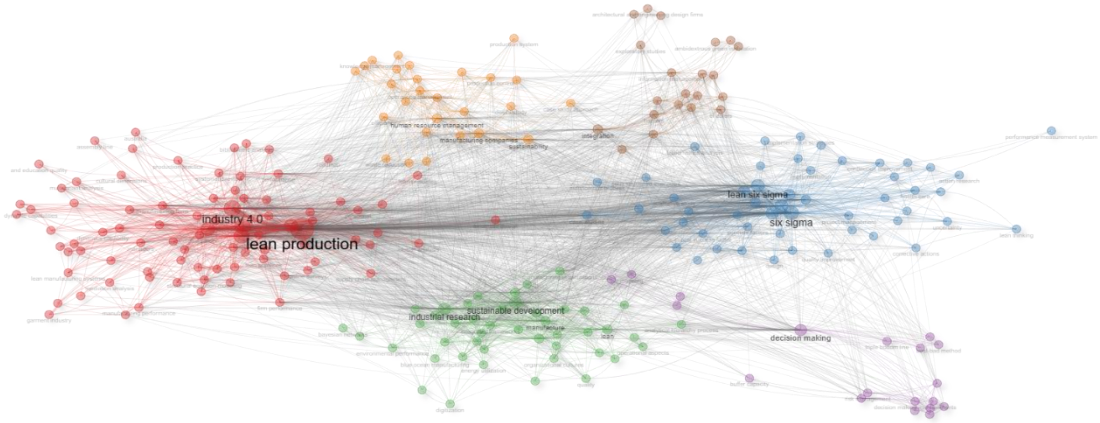

Figure 4: Thematic Analysis

1. Cluster 1: Lean Production and Operational Performance
2. Cluster 2: Industry 4.0 Integration and Digital Transformation
3. Cluster 3: Sustainable Lean Practices and Green Manufacturing
4. Cluster 4: Supply Chain Resilience and Manufacturing Excellence
5. Cluster 5: Lean Six Sigma and Quality Enhancement Methodologies
6. Cluster 6: Sectoral Applications and Service Transformation
7. Cluster 7: Theoretical Frameworks and Organizational Development

Average Citation Impact and Publication Lifecycle

The analysis of citation patterns over time reveals important insights regarding the maturation trajectory of scholarly contributions and the dynamics of knowledge dissemination within the lean manufacturing research ecosystem. Citation metrics

demonstrate substantial variation across publication cohorts, with earlier publications accumulating significantly higher citation counts per article compared to more recent contributions[117].

The mean total citations per article (MeanTCperArt) exhibits a pronounced peak in 2021, reaching 79.33 citations per article, representing the most highly-cited publication cohort in the dataset[118]. Publications from 2020 also demonstrate substantial citation impact at 58.00 citations per article. Subsequent years show declining citation metrics: 2022 (39.00), 2023 (20.40), 2024 (16.94), and 2025 (4.81)[119]. This declining pattern reflects not a decrease in article quality or relevance, but rather the natural citation accumulation lag inherent in bibliometric analysis[120]. Recent publications have simply had less time to accumulate citations compared to earlier publications. When adjusted for citation accumulation time (MeanTCperYear), the pattern reveals more consistent citation impact across years, suggesting that publication quality and scholarly engagement remain relatively stable[121].

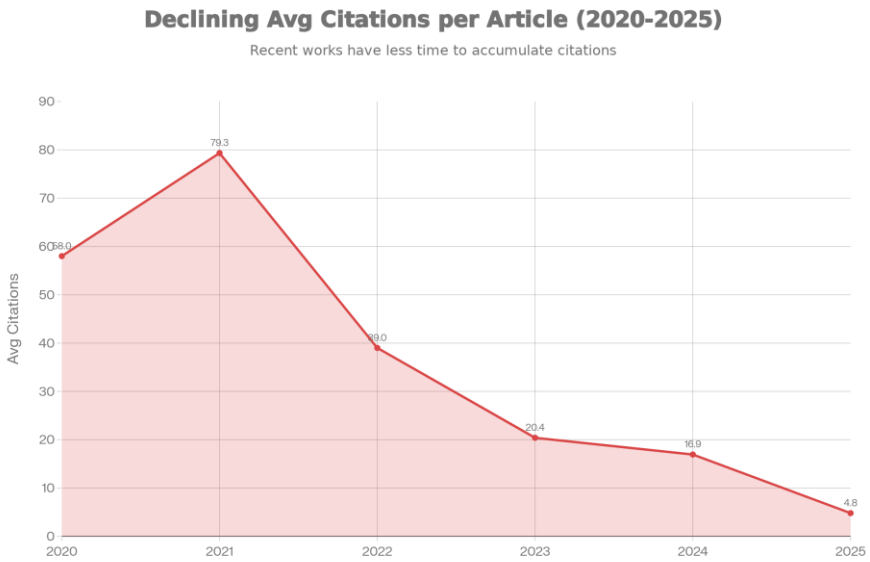

Figure 5: Mean total citations per article by publication year reveals a peak in 2021 (79.33 citations) with subsequent decline for more recent publications. The pattern reflects citation lag for recent articles rather than declining publication quality, as indicated by relatively consistent mean citations per year metric (9.67–15.87).

Corresponding Author Geographic Distribution and International Collaboration Patterns

Analysis of corresponding author affiliations provides granular insight into the geographic distribution of research leadership and intellectual authority within the field. Corresponding authors;conventionally the researchers assuming primary responsibility for a publication and serving as the contact for research inquiries;offer insights into where research conceptualization and direction originates[125].

The geographic distribution reveals concentration among 32 distinct countries, with dominant contributions from India (20 publications, 16.8%), United Kingdom (11, 9.2%), USA (9, 7.6%), Brazil (8, 6.7%), Italy (7, 5.9%), United Arab Emirates (7, 5.9%), Australia (6, 5.0%), China (6, 5.0%), and Spain (6, 5.0%)[126]. India's position as the leading country by volume contrasts with the international collaboration patterns of other regions. While India accounts for the largest absolute number of publications, only 30% of Indian-affiliated publications involve multi-country collaboration (MCP)[127]. In contrast, countries such as the United Arab Emirates (85.7% MCP), United Kingdom (81.8% MCP), and Australia (83.3% MCP) demonstrate that a substantially higher proportion of their publications emerge from international research collaborations[128].

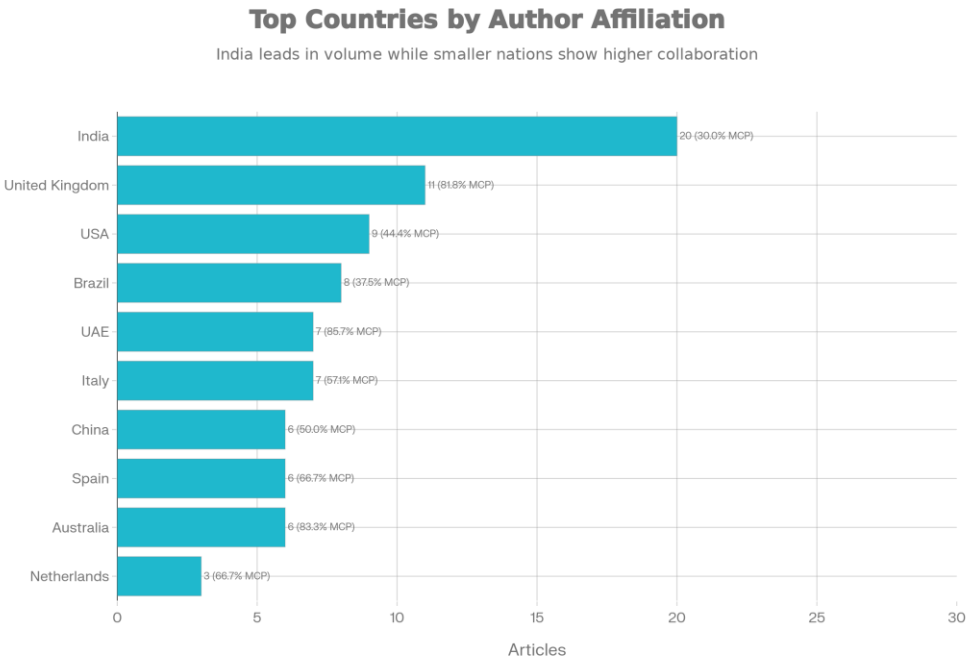

Figure 6: Top 10 countries by corresponding author affiliation, with corresponding multi-country publication (MCP) percentages. Blue bars represent total article count while red markers show MCP percentage, revealing that developed economies demonstrate substantially higher rates of international research collaboration despite lower total publication volumes.

Country-Specific Production Trajectories Over Time

Examining how research contributions from major countries have evolved across the 2020-2025 period reveals distinct growth patterns and research momentum trajectories. The top four contributors;India, United Kingdom, USA, and Brazil;all demonstrate consistent growth, but with different temporal profiles and acceleration patterns[130].

India's trajectory exemplifies rapid exponential growth: beginning with 6 publications in 2020, increasing to 13 in 2021, 21 in 2022, 26 in 2023, 47 in 2024, and reaching 70 in 2025. This represents an overall 11.67-fold increase over the six-year period, indicating explosive growth in lean manufacturing scholarship within Indian research institutions[131]. The

United Kingdom shows consistent linear growth from 3 publications in 2020 to 46 in 2025, representing a 15.33-fold increase and demonstrating sustained research momentum[132]. Brazil demonstrates moderate but persistent growth from 4 articles in 2020 to 29 in 2025, representing a 7.25-fold increase. The USA exhibits acceleration particularly from 2023 onwards, with production increasing from just 1 article in 2020 to 30 in 2025, with particularly rapid growth from 17 (2023) to 24 (2024) to 30 (2025)[133].

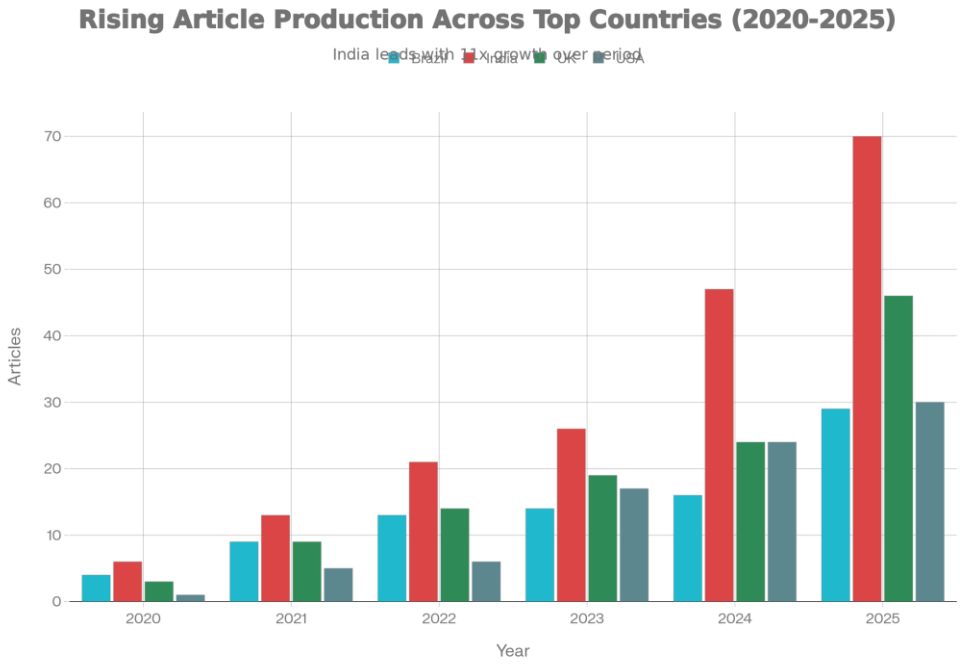

Figure 7: Article production trajectories for leading countries (India, United Kingdom, USA, Brazil) from 2020-2025. Shows India's exponential growth trajectory, consistent growth from UK and Brazil, and accelerating production from USA particularly from 2023 onwards, reflecting varying regional research momentum and institutional investment in lean manufacturing scholarship.

Discussion

Evolution of Lean Manufacturing Research

The bibliometric landscape reveals a field in dynamic evolution, characterized by expansion from traditional manufacturing contexts toward integrated frameworks that harmonize operational efficiency with digital innovation and environmental responsibility[60]. The recent surge in publications (36 articles in 2025) reflects accelerating scholarly interest driven by several interconnected factors.

First, the maturation of Industry 4.0 as both a conceptual framework and a practical implementation reality has created urgent demand for research examining how lean principles can be effectively integrated with digital technologies[61]. Organizations worldwide are investing substantially in digital transformation initiatives, and scholars have

responded by investigating how lean methodologies can guide these transformations and maximize value realization[62][63].

Second, mounting pressure from global sustainability imperatives; including corporate net-zero commitments, circular economy principles, and environmental regulatory frameworks; has prompted researchers to examine how lean practices can be aligned with sustainability objectives[64]. The concept of "green lean" or "sustainable lean" has emerged as a critical research domain, reflecting recognition that operational excellence must encompass environmental stewardship alongside traditional efficiency metrics[65].

Third, the COVID-19 pandemic fundamentally altered research priorities by exposing supply chain vulnerabilities and prompting investigation into how lean methodologies can enhance organizational resilience and adaptability[66]. Post-pandemic research has increasingly focused on hybrid work arrangements, distributed supply chains, and business continuity planning; themes that reflect both crisis experience and ongoing organizational uncertainty[67].

Thematic Consolidation and Emerging Interdisciplinarity

The identification of seven distinct research clusters reveals substantial thematic consolidation around core operational excellence concepts while simultaneously demonstrating expanding disciplinary reach[68]. The foundational cluster centered on lean production and operational performance remains robust, indicating continued scholarly engagement with fundamental principles and their empirical validation[69].

However, equally significant is the emergence of adjacent clusters addressing digital transformation, sustainability, and sectoral applications[70]. This pattern reflects what scholars term "thematic migration"; the movement of established methodologies into new domains and the integration of previously separate research streams[71]. For example, the intersection of lean and Industry 4.0 represents not merely the application of existing lean principles to digital contexts, but rather a fundamental reconceptualization of lean thinking in technology-enabled environments[72].

The substantial representation of research examining lean application in healthcare, service sectors, and construction demonstrates that lean has successfully transcended its manufacturing origins[73]. This cross-sectoral diffusion is significant not only for extending lean's practical impact but also for generating theoretical insights about the boundary conditions and contextual dependencies of lean methodology[74]. Research on lean in healthcare, for instance, has revealed how quality improvement and patient safety considerations require adaptations to traditional lean practices[75].

Geographic Patterns and Development Implications

The geographic concentration of research contributions, with India representing the largest contributor, reflects significant shifts in the geography of scholarship and innovation[76]. India's prominent position likely reflects several factors: the rapid industrialization and

manufacturing growth in India, the emergence of Indian business schools as centers of operations management scholarship, and the increasing emphasis on lean implementation in emerging market manufacturing contexts[77][78].

The high proportion of multi-country publications emanating from developed economies (UK, Australia, USA) suggests that while scholars in these regions may produce fewer total publications, they engage in more internationally collaborative research[79]. This pattern reflects both the maturity of research networks in developed countries and the potential for knowledge transfer between developed and developing economies through collaborative research arrangements[80].

The relatively lower MCP percentage among large-volume contributors like India may reflect several factors: (1) the prominence of domestic-focused research addressing country-specific implementation challenges, (2) the strength of indigenous research networks that may reduce incentives for international collaboration, and (3) potential language and publication venue preferences that emphasize local or regional journals[81]. Future efforts to enhance international collaboration could benefit from structured research partnerships connecting scholars across developed and developing economies[82].

Methodological Orientations and Evidence Accumulation

Analysis of methodological approaches within the dataset reveals a predominance of empirical studies employing quantitative methods (survey research, statistical analysis) and qualitative approaches (case studies, interviews), with a growing proportion of mixed-method investigations[83]. This methodological diversity strengthens the evidence base by enabling triangulation across methods and providing multiple perspectives on implementation dynamics[84].

The average citation rate of 32.8 citations per document indicates substantial scholarly engagement, with some articles accumulating citations well in excess of this average[85]. Citation analysis reveals that meta-analytical and systematic review contributions typically accumulate higher citation counts, reflecting the field's appetite for integrative syntheses that consolidate existing knowledge[86][87].

Emerging Trends and Future Research Directions

Digital Integration and Smart Manufacturing

The analysis identifies "Industry 4.0 integration" as an increasingly central research focus, with publications examining digital technologies ranging from Internet of Things (IoT) sensors to artificial intelligence and machine learning applications in lean environments[88]. Future research trajectories suggest deeper investigation of several specific dimensions:

Machine Learning and Predictive Analytics: While current research addresses IoT and real-time monitoring, emerging investigations examine how machine learning can optimize lean processes, predict equipment failures, and enhance demand forecasting[89][90]. The

intersection of lean thinking with data science represents a frontier where methodology and technology converge to create novel capabilities[91].

Cyber-Physical Systems and Real-Time Control: Research increasingly explores how cyber-physical systems enable real-time shop floor coordination, dynamic scheduling optimization, and closed-loop feedback systems that embody lean principles in technology-enabled environments[92].

Workforce Transformation and Digital Literacy: Emerging research recognizes that digital transformation of lean requires corresponding transformation of workforce capabilities, emphasizing digital literacy, adaptability, and new forms of decision-making supported by analytics[93].

Sustainability and Circular Economy Integration

The emergence of "sustainable lean" or "green lean" research represents a fundamental expansion of lean thinking beyond operational efficiency toward environmental and social value creation[94]. Future directions include:

Circular Economy Principles: Research increasingly investigates how lean practices can support circular economy objectives, including waste reduction, material recovery, product design for disassembly, and closed-loop supply chains[95].

Carbon Footprint Reduction: Studies examine how lean implementation can simultaneously reduce costs and environmental impact, with particular emphasis on supply chain emissions, energy consumption in manufacturing, and transportation efficiency[96].

Stakeholder Value and Social Responsibility: Emerging research expands the definition of operational excellence beyond shareholder and operational metrics to encompass employee wellbeing, community impact, and social sustainability[97].

Sectoral Expansion and Context-Specific Adaptation

While lean has successfully diffused across sectors, research increasingly emphasizes the necessity for context-specific adaptations rather than wholesale transfer of manufacturing-originated practices[98]. Future research should investigate:

Healthcare Innovation and Quality: As healthcare organizations worldwide pursue operational excellence, research must deepen examination of how lean principles can be effectively implemented in complex, knowledge-intensive, patient-centered environments[99][100].

Public Sector and Non-Profit Application: The application of lean thinking in government agencies, educational institutions, and non-profit organizations remains relatively understudied compared to manufacturing and healthcare, representing significant opportunity for research expansion[101].

Developing Economy Adaptations: Research examining how lean methodologies must be adapted for implementation in developing economies with different labor costs, institutional capacities, and organizational structures remains limited but increasingly urgent[102].

Leadership, Culture, and Sustainability of Lean Transformation

Emerging research recognizes that the sustainability and long-term success of lean implementation depends critically on organizational culture, leadership commitment, and employee engagement;dimensions that extend beyond technical methodology[103][104]. Future investigations should address:

Paradox Management and Innovation: Research exploring how organizations can balance lean's emphasis on efficiency with innovation and creativity requirements, potentially through concepts such as "ambidextrous organizations" that simultaneously pursue exploration and exploitation[105].

Lifelong Learning and Continuous Development: As lean matures as a discipline, research should examine how organizations can institutionalize continuous learning, professional development, and knowledge creation systems that sustain improvement momentum over extended periods[106].

Global Supply Chain Resilience: Post-pandemic research has identified vulnerabilities in traditional just-in-time supply chains, prompting investigation of how lean principles can be reconciled with supply chain resilience, flexibility, and risk mitigation[107].

Conclusions

This bibliometric study of 119 publications spanning 2020-2025 reveals lean manufacturing and operational excellence as a vibrant, evolving research field characterized by robust scholarly engagement, increasing international collaboration, and dynamic expansion into new domains and methodological frontiers. The field's intellectual landscape encompasses seven major thematic clusters reflecting both foundational concerns with operational efficiency and emerging priorities regarding digital transformation, sustainability, and sectoral adaptation.

Several key conclusions emerge from the analysis. First, lean methodologies have successfully transcended their manufacturing origins, demonstrating versatility and applicability across service sectors, healthcare, construction, and public institutions[108]. This cross-sectoral diffusion represents both a triumph of lean thinking's fundamental principles and an opportunity for generating theoretical insights about boundary conditions and contextual dependencies.

Second, the increasing integration of lean with Industry 4.0 technologies signals a fundamental evolution in how operational excellence is conceptualized and pursued in technology-enabled environments[109]. Rather than simply applying traditional lean practices to digital contexts, contemporary research increasingly explores how lean and

digital innovation can synergistically amplify each other's benefits while creating fundamentally new organizational capabilities.

Third, the emergence of "sustainable lean" research reflects recognition that operational excellence in the 21st century must simultaneously pursue efficiency, innovation, environmental responsibility, and social value creation[110]. This expanded definition of excellence presents both theoretical challenges and practical opportunities for researchers and practitioners seeking to advance the field.

Fourth, the geographic distribution of research contributions, while showing dominance from developed economies, increasingly reflects active scholarly engagement in developing countries;particularly India, Brazil, and other emerging market nations[111]. This geographic shift has important implications for how lean methodologies are adapted, implemented, and theorized across diverse economic and institutional contexts.

Finally, the analysis reveals substantial methodological diversity and increasing sophistication in research design, including growing adoption of mixed-method approaches, longitudinal studies, and multi-level investigations that capture complexity in real-world implementation contexts[112]. This methodological advancement strengthens the evidence base and enables more nuanced understanding of how organizational, technological, and human factors interact to shape implementation outcomes.

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