

Border Technologies in International Trade: Evolution, Asymmetries, and Future Research Frontiers-A Bibliometric Analysis (2009-2025)

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ABSTRACT

This study conducts a bibliometric analysis of 432 publications on international trade and border technologies (2009-2025), drawing on Scopus and Web of Science databases. Findings reveal a two-phase trajectory: stagnation pre-2020, followed by accelerating growth (CAGR: 14.2%) driven by COVID-19 and geopolitical disruptions. Research is geographically concentrated, with China, the United States, and the United Kingdom dominating output. Keyword co-occurrence analysis identifies two clusters: digital trade infrastructure and macroeconomic trade determinants. Critical gaps persist around border governance, digital sovereignty, and environmental sustainability. The study proposes interdisciplinary research directions spanning political, social, and economic dimensions of border technology deployment.

Keywords: Bibliometric Analysis, Border Technologies, International Trade, Knowledge Mapping, Research Trends.

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INTRODUCTION

In a world where trillions of dollars' worth of goods are exchanged across borders each year, international trade has been of paramount importance since ancient times. It drives global economic integration by facilitating the exchange of goods, services, and ideas. Over time, international trade has evolved through various stages, culminating in the current era of accelerated globalization, which has reshaped the international trade landscape to become more complex and interconnected (Khan, 2024). This era is characterized by innovative technologies and digital infrastructure, driven by the need to increase efficiency, improve speed, and reduce costs (Bellucci *et al.*, 2025). These factors have accelerated the adoption of emerging technologies in international trade and their integration into cross-border transactions. This evolution has led to the emergence of "border technologies," which arise from the interaction between technology and various border operations. The applications of border technologies extend beyond regulating and monitoring goods in international trade; they also encompass managing and tracking human movement through biometric systems, digital platforms, and automated border control gates. These technologies

aim to ensure compliance and enhance security (Amelung and Galis, 2023). More precisely, the term "border technologies" as used in this study refers to a broad spectrum of technological systems deployed at or beyond physical border checkpoints to regulate the cross-border movement of goods, persons, and data. This encompasses three overlapping categories: (1) identification and biometric technologies, including fingerprint scanners, facial recognition systems, machine-readable travel documents, and automated border control gates; (2) information and surveillance infrastructures, such as large-scale databases (e.g., customs management systems, cargo tracking platforms), unmanned aerial vehicles (drones), satellite-based monitoring systems, and sensor networks; and (3) digital trade facilitation tools, including blockchain-based customs automation, artificial intelligence-driven risk assessment engines, and the Internet of Things (IoT) applications integrated into supply chain management (Amelung and Galis, 2023; Martins and Jumbert, 2020; Milivojevic, 2017). While these categories were originally developed in distinct disciplinary traditions (trade economics, border security studies, and migration governance), their convergence in contemporary border environments justifies their treatment as a unified conceptual domain for the purposes of bibliometric mapping. This operationalization allows the study to capture both the efficiency-oriented dimension of border technologies (facilitating legal trade flows) and their governance and surveillance dimension (monitoring and controlling movement), thereby reflecting the dual character of modern border infrastructure.



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Border technologies have contributed to the development and improvement of border transactions, particularly in the context of international trade, making them faster, more efficient, and less costly (Wang and Choi, 2019). Global trade has steadily grown to unprecedented levels, reaching a record high of \$32 trillion in 2022, declining slightly in 2023, and then surpassing the previous record with \$33 trillion in 2024 (UN Trade and Development, 2024). This growth has presented numerous challenges for both developing and developed countries. Notably, climate change has become a major concern, as international trade contributes significantly to global carbon emissions through logistics, transportation, and resource-intensive supply chains (Cabernard *et al.*, 2025). Consequently, sustainability has emerged as one of the most pressing issues in this context.

The intersection of international trade and border technologies represents a rapidly evolving research frontier shaped by global crises, technological innovation, and shifting geopolitical priorities. From the post-2008 recovery to the COVID-19 pandemic and the rise of the Fourth Industrial Revolution, this period has witnessed a surge in digital infrastructure development and trade automation. Yet, scholarly output remains modest and fragmented, particularly in the technological dimension. There is a clear focus on topics such as blockchain applications (Chang *et al.*, 2019; Chang *et al.*, 2020), Sustainability, and Carbon Reduction (Atkinson *et al.*, 2011; Feng *et al.*, 2013; Tian *et al.*, 2022).

This study aims to explore the political, social, and economic implications of border technologies in international trade, identifying emerging research areas and interdisciplinary gaps. The current work research objectives included: 1) To analyze the political strategies and governance models driving border technology adoption in global trade; 2) To assess the social consequences of digital border systems, including equity, migration, and public trust; 3) To evaluate the economic impact of emerging technologies (e.g., blockchain, AI, IoT) on trade efficiency, sustainability, and resilience; 4) To identify underexplored themes and propose new interdisciplinary research directions. This research addresses a critical gap in the literature by moving beyond technical applications to explore the broader systemic impacts of border technologies. It offers a timely contribution to debates on digital governance, trade justice, and global sustainability, especially as nations recalibrate their trade strategies in response to climate change, cyber threats, and shifting alliances.

In addressing these objectives, we provide answers to the following research questions: 1) What is the yearly distribution of publications on international trade and border technologies over the past 16 years? 2) What are the most relevant journals in international trade and border technologies? 3) Which countries and institutions are the most productive in international trade and border technologies? 4) What are the most cited

and influential publications in international trade and border technologies? 5) What emerging trends in international trade and border technologies are reflected by keyword co-occurrences in literature?

This study offers a novel contribution by reframing border technologies not merely as technical instruments of trade facilitation but as complex socio-political infrastructures with far-reaching implications for governance, equity, and sustainability. By integrating bibliometric analysis with a critical lens on digital transformation, the research uncovers how scholarly discourse has evolved in response to global disruptions (from the 2008 financial crisis to the COVID-19 pandemic and the rise of algorithmic governance). Unlike prior studies that focus narrowly on operational efficiency or isolated technological applications, this work maps the interdisciplinary convergence of trade, migration, and digital sovereignty, revealing underexplored themes such as the environmental role of border systems and the digital divide between nations. The study's taxonomy of emerging trends and its reflexive approach to bibliometric visibility provide a foundation for anticipatory governance and inclusive policy design, positioning it as a timely resource for scholars and decision-makers navigating the complexities of global commerce in a digitally mediated world.

The rest of the work develops as follows. Materials and methods are presented in Section 2. Section 3 presents findings based on each of the previously pointed research questions, and the findings are discussed in Section 4. Section 5 presents our results from the bibliometric analysis of the implications and emerging research areas, whereas Section 6 concludes this work.

METHODOLOGY

This study employs bibliometric analysis, a widely recognized research method in scientific circles. This approach provides a quantitative perspective on scientific literature within a specific field by examining the main contributors, institutions, and research trends. Bibliometric analysis can yield valuable insights into research gaps and opportunities (Öztürk *et al.*, 2024). However, it is important to acknowledge and understand its limitations to interpret the results accurately.

The initial search

This study presents a bibliometric analysis of research related to the variables "International Trade" and "Border Technologies." The analysis was conducted on 08/01/2026 using the SCOPUS and Web of Science databases, applying the search query TITLE-ABS-KEY (international trade and border technologies). The initial search returned 975 documents from Scopus and 496 documents from WoS.

The search terms were selected based on two criteria. First, "international trade" was chosen as the primary conceptual

anchor, given its established use in economics and policy literature to describe cross-border exchange of goods and services. Second, "border technologies" was selected as the complementary term to capture the technological dimension of border operations, encompassing digital infrastructure, customs automation, biometric systems, and surveillance technologies deployed at trade borders. The conjunction of both terms was intentional, as the study specifically targets the intersection of these two domains rather than either in isolation. No synonyms or alternative terms were added at this stage in order to maintain conceptual precision and avoid retrieving literature peripheral to the core research focus. It is worth noting that "border technologies" as a search term is consistent with its scholarly usage as an umbrella concept covering both trade-facilitation technologies and migration-control technologies (Amelung and Galis, 2023; Martins and Jumbert, 2020). The term was preferred over narrower alternatives (e.g., "customs automation" or "smart borders") in order to allow the corpus to reflect the full range of scholarship that self-identifies with this intersection, while the subsequent analysis remains anchored to publications addressing international trade as their primary domain.

Exclusion Criteria

To exclude results outside the scope of our research, we first used the automatic exclusion settings available in the Scopus and Web of Science databases. After this initial step, we reviewed the remaining results to ensure their quality and relevance, manually excluding any documents that did not fit the context of our study.

Automatic exclusion

The first step in applying exclusion criteria is to determine the study's timeframe. For this research, the period from 2009 to 2025 was selected for two main reasons. First, the aftermath of the 2008 global financial crisis sparked increased interest in trade facilitation, leading to more research in this area. Second, this period encompasses the emergence and development of new technologies, particularly those adopted in international trade and border technologies.

Scopus

We restricted the results to English-language publications (LIMIT-TO (LANGUAGE, "English")). The subject areas included social sciences, economics, computer science, business, and decision science (LIMIT-TO (SUBJAREA, "SOC") OR LIMIT-TO (SUBJAREA, "ECON") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "DECI")). We excluded engineering and medical sciences from our search because they were outside the scope of our research focus. Finally, we limited the search to articles (LIMIT-TO (DOCTYPE, "ar")) and excluded conference papers, book chapters, books, conference reviews, reviews, editorials,

withdrawn, or corrected articles. After applying these exclusion criteria, the results were filtered to 295 studies.

WoS

Similarly, we applied exclusion criteria to the Web of Science database. For language, we limited the results to English only. Regarding subject areas, the Web of Science database provided more specific and accurate classifications, offering a wide range of detailed specializations. Therefore, we limited the results to categories such as Economics or International Relations or Management or Law or Business or Business Finance or Computer Science Information Systems or Energy Fuels or Green Sustainable Science Technology or Information Science Library Science or Multidisciplinary Sciences or Geography or Telecommunications or Engineering Industrial or Political Science or Engineering Electrical Electronic or Operations Research Management Science or Social Sciences Interdisciplinary or Computer Science Interdisciplinary Applications or Criminology Penology or Development Studies or Engineering Multidisciplinary or Public Administration or Transportation or Communication or Computer Science Artificial Intelligence or Geosciences Multidisciplinary or Materials Science Multidisciplinary or Mathematics Interdisciplinary Applications or Social Issues or Computer Science Theory Methods or Transportation Science Technology or Social Work or Social Sciences Mathematical Methods or Instruments Instrumentation (Web of Science Categories).

Finally, we limited the results to documents of Article (Document Types) only. The results were filtered to 313 studies after applying the exclusion criteria.

Manual exclusion

Although we applied all available automatic exclusion criteria in the Scopus and Web of Science databases, this was not sufficient to obtain accurate results. We manually verified the remaining articles (title and abstract) within each database independently to exclude those unrelated to our topic. After manual review, we removed 23 articles from the Scopus database and 25 from the Web of Science database (48 articles excluded for lack of topical relevance). As a result, the final search yielded 272 articles in Scopus and 288 in Web of Science.

Merge Scopus and WoS and Duplication Removal

Because many publications are indexed in both Scopus and Web of Science, there is significant overlap between the two databases. To ensure the reliability of our results, which depends on the integrity and uniqueness of the final dataset, we cleaned and deduplicated the data using the R programming language (version 4.5.1) and RStudio (version 2025.05.1+513). This process removed 128 duplicate records (i.e., articles appearing in both databases). It is important to note that these 128 duplicates are distinct from the 48 articles manually excluded during title-and-abstract

screening within each database (Section 2.2.2); the former reflects inter-database overlap, whereas the latter reflects intra-database topical exclusion. Figure 1 provides a Prisma 2020 flow diagram adapted for bibliometric analysis (Page *et al.*, 2021).

Data analysis and visualization

Data analysis and visualization were conducted using Biblioshiny, an interactive web-based application built on the bibliometrix R package. This tool offers comprehensive bibliometric analysis and intuitive visualizations through a wide range of analytical features, including descriptive statistics, citation analysis, network mapping, and thematic exploration—all specifically designed for bibliographic datasets (Mondal, 2025). We used Biblioshiny to uncover trends and patterns in research related to international trade and border technologies. In this context, Biblioshiny enabled us to perform repeatable and efficient analyses, ensuring high-quality outputs that accurately represent the intellectual landscape of this field. This approach allowed us to identify influential works, key contributors, and emerging research topics within the compiled literature.

Findings

This study aims to present a profile of research on international trade and border technologies over the past 16 years (the study time frame starts from the year 2009 to 2025). The findings are discussed in relation to the research questions.

Research Question 01

What is the yearly distribution of publications on international trade and border technologies over the past 16 years?

To address the first research question, we analyzed the publication years of articles from the past 16 years using data from the Scopus and Web of Science databases.

As shown in Figure 2, the annual scientific output on the intersection of international trade and border technologies spans 2009 to 2025, yielding a corpus of 432 publications. Over this period, production followed a two-phase trajectory. The first phase (2009–2019) was characterised by relative stagnation, with annual output fluctuating between 5 and 19 articles and averaging 13.3 publications per year, reflecting the nascent and fragmented nature of the field. A pronounced inflection point emerged in 2020, marking the onset of a sustained and accelerating growth phase, during which annual output rose from 21 articles in 2020 to 92 in 2025 a fourfold increase within five years with an average of 46.5 publications per year. The overall Compound Annual Growth Rate (CAGR) for the full period stands at 14.2%, with the growth rate intensifying markedly after 2021, most notably between 2024 and 2025, when output surged by 58.6%.

Research Question 02

What are the most relevant journals in international trade and border technologies?

As shown in Figure 3, analysis of publication venues reveals that the 432 articles comprising this corpus are distributed across a wide range of journals, with no single outlet commanding a dominant share—an observation consistent with the interdisciplinary character of the field. Among the ten most productive sources, the Journal of World Trade leads with 18 articles (4.2% of the total corpus), followed by World Economy ($n=7$) and a cluster of four journals Energy Economics, Global Trade and Customs Journal, Journal of International Economics, and the Journal of International Trade and Economic Development each contributing 6 articles. A second cluster comprises Journal of Cleaner Production, Mobile Information Systems, Sustainability, and Technological Forecasting and Social Change, each with 5 publications. Collectively, these ten journals account for 69 articles, representing 16.2% of the corpus, indicating that the vast majority of relevant scholarship is dispersed across a broader publishing landscape.

Research Question 03

Which countries and institutions are the most productive in international trade and border technologies?

As shown in Table 1, the geographic distribution of scholarly contributions reveals a pronounced concentration of research output among a small number of countries. China leads by a substantial margin with 317 articles (40.6% of the total 780 recorded country-level contributions), followed by the United States ($n=161$; 20.6%) and the United Kingdom ($n=66$; 8.5%), with the top three collectively accounting for nearly 70% of all contributions. The remaining positions in the top ten are occupied by India ($n=42$), Germany ($n=39$), Australia ($n=36$), Japan ($n=33$), Canada and Ukraine ($n=30$ each), and South Korea ($n=26$).

Analysis by corresponding authorship in Table 2 reinforces this hierarchy: China's researchers served as corresponding authors on 113 articles (26.2% of the full corpus), followed by the United States ($n=49$; 11.3%) and the United Kingdom ($n=22$; 5.1%), with Malaysia emerging as a notable presence ($n=9$) despite its absence from the general production rankings. Examination of collaboration patterns reveals significant cross-national variation in research orientation: Germany and the United Kingdom exhibit the highest rates of internationally co-authored output, with Multi-Country Publication (MCP) rates of 50.0% and 40.9% respectively, while India records a 0% MCP rate, indicating a wholly domestically oriented research programme. China and the United States, despite their output dominance, display comparatively modest MCP rates of 17.7% and 22.4%.

Research Question 04

What are the most cited and influential publications in international trade and border technologies?

After identifying the countries and institutions that lead research in international trade and border technologies, this section provides a deeper and more comprehensive understanding by discussing the most cited documents.

Table 3, which lists the seven most globally cited publications in the corpus accumulate 1,768 citations in total, spanning work published between 2010 and 2022 and distributed across seven distinct journals. The most cited work is (Feng *et al.*, 2013) with 565 total citations and an annual rate of 40.36, followed by (Chang *et al.*, 2020) with 393 citations and the highest normalised citation score in the list (TC/year=56.14; normalised TC=11.31) (Graaf *et al.*, 2020). Ranks third with 216 citations, while (Manova and Yu, 2016; Picci, 2010; Jafari-sadeghi *et al.*, 2022) contribute 172, 150 and 137 citations respectively the latter recording the second-highest normalised score (10.22) despite its recent publication date (Nahm, 2014), with 135 citations and a normalised TC of 6.32, rounds out the list as the sole entry focused on manufacturing specialisation and industrial upgrading. Three

of the seven papers were published before 2015, one between 2015 and 2019, and three from 2020 onward. Thematically, the most influential works cluster around three areas: global supply chain structure, resilience, and embedded carbon flows (Chang *et al.*, 2020; Feng *et al.*, 2013; Manova and Yu, 2016); energy security, geopolitics and the internationalisation of innovation (Graaf *et al.*, 2020; Picci, 2010; Graaf *et al.*, 2020; Picci, 2010); and the digitalisation of trade and the dynamics of innovative manufacturing (Chang *et al.*, 2019; Jafari-sadeghi *et al.*, 2022).

Research Question 05

What emerging trends in international trade and border technologies are reflected by keyword co-occurrences in the literature?

Figure 4 presents a network analysis of keyword co-occurrence in international trade and border technology research from 2009 to 2025, constructed from 51 nodes distributed across two distinct clusters, reveals a bifurcated yet interconnected intellectual structure. The dominant node across the entire network is international trade (betweenness centrality=304.09; PageRank=0.083), which functions as the primary structural bridge between the two clusters. The first cluster (red, 16 nodes)

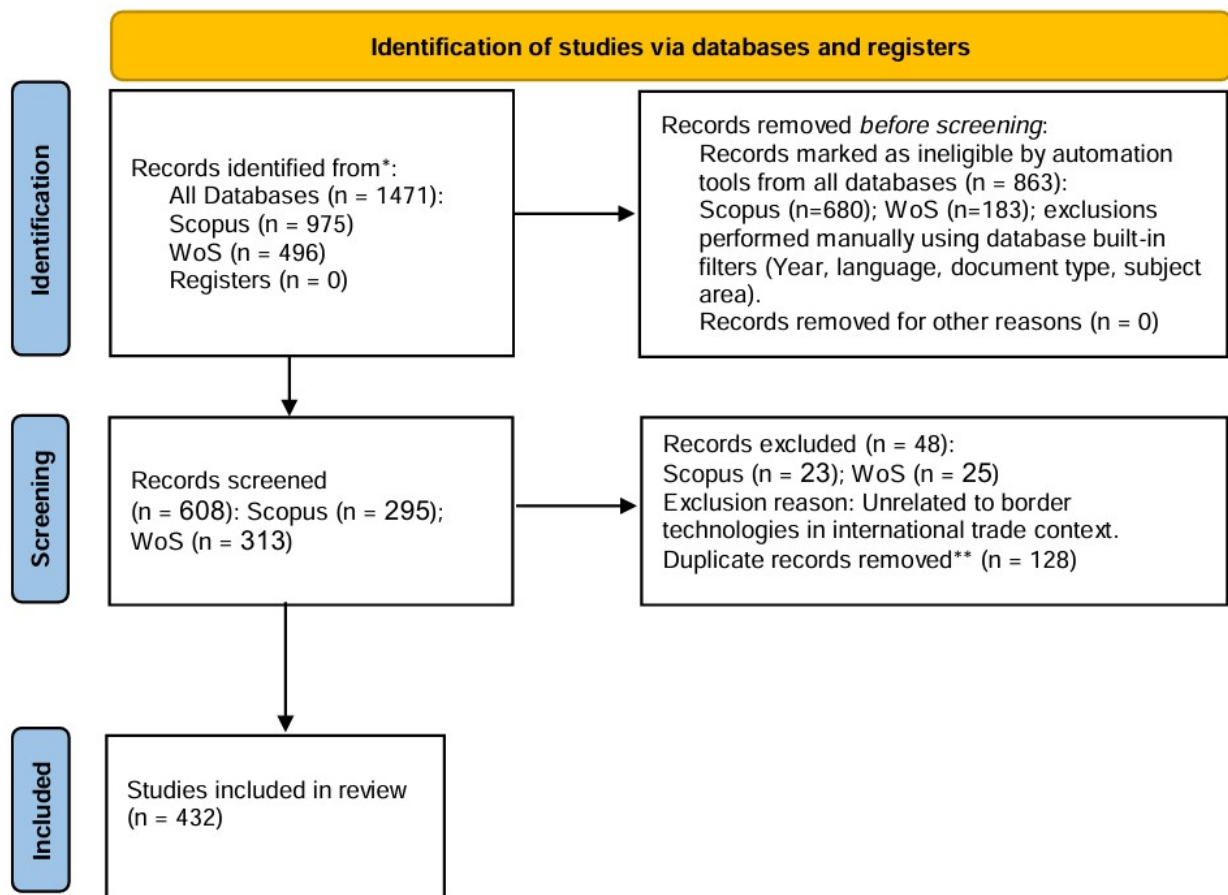


Figure 1: Prisma 2020 flow diagram adapted for bibliometric analysis. **Note: In this study, deduplication was performed after database-level filtering using R Studio (v4.5.1), following independent screening within each database. This reflects the standard workflow in bibliometric research, where records are downloaded separately from each database before merging and deduplication.

Table 1: Countries' Scientific Production.

Country	Freq	Country	Freq
CHINA	317	AUSTRALIA	36
USA	161	JAPAN	33
UK	66	CANADA	30
INDIA	42	UKRAINE	30
GERMANY	39	SOUTH KOREA	26

Source: Author's creation using Biblioshiny, based on Scopus and WoS databases.

Table 2: The most productive countries in International Trade and Border technologies.

Rank	Country	Articles	Articles %	SCP	MCP	MCP %
1	CHINA	113	26,2	93	20	17,7
2	USA	49	11,3	38	11	22,4
3	UNITED KINGDOM	22	5,1	13	9	40,9
4	INDIA	18	4,2	18	0	0
5	KOREA	12	2,8	11	1	8,3
6	CANADA	11	2,5	10	1	9,1
7	GERMANY	10	2,3	5	5	50

Source: Author's creation using Biblioshiny, based on Scopus and WoS databases.

coalesces around the digitalisation of cross-border commerce, with cross-border e-commerce (betweenness=20.14), cross-border (10.73), and internet (10.31) as its most central terms, alongside blockchain, artificial intelligence, electronic commerce, digital trade, logistics, and security-collectively delineating a research stream focused on the technological infrastructure and regulatory governance of digital trade flows. The second cluster (blue, 34 nodes) is structurally denser and anchored by technology (betweenness=196.96; PageRank=0.074), trade (185.45; 0.074), innovation (46.47), and international-trade (95.71), with a broad constellation of terms including productivity, FDI, competition, economic growth, R&D, competitiveness, gravity model, CO₂ emissions, governance, and trade facilitation-reflecting a more established stream concerned with the macroeconomic and structural determinants of trade performance and technology-driven growth.

DISCUSSION

The findings of this bibliometric analysis collectively map an intellectual field in rapid but uneven transition one that has grown substantially in volume while remaining structurally fragmented in its conceptual foundations, geographic reach, and disciplinary identity. Interpreting these findings in relation to the study's five research questions reveals a coherent narrative of emergence, institutionalisation, and persistent gaps that carries important implications for scholars, practitioners, and policymakers' implications developed in depth in Section 5.

Growth Dynamics and Institutional Drivers

The two-phase trajectory in annual output stagnation between 2009 and 2019, followed by accelerating growth from 2020 onward, is structurally determined rather than incidental. The pre-2020 plateau reflects the typical dynamics of nascent interdisciplinary fields: in the absence of a consolidated theoretical framework or a recognised community of practice, research at the intersection of trade economics and border technology remained largely peripheral to both parent disciplines. The inflection triggered in 2020 is best understood as the product of simultaneous exogenous shocks that elevated border systems from an operational concern to a strategic priority. The COVID-19 pandemic exposed systemic vulnerabilities in cross-border logistics and supply chain governance, generating urgent demand for research on digital and automated border management. Concurrently, the escalation of US-China trade tensions and the broader fragmentation of the multilateral trade order recast border technologies as instruments of economic statecraft, attracting scholars from international relations, political economy, and public policy. China's Belt and Road Initiative, in particular, has been cited in policy literature as an illustration of how digital border infrastructure may function as a vector of geopolitical influence (Polyakova and Meserole, 2019), a dimension whose scholarly implications extend well beyond bibliometric growth trends into the political and normative questions explored in Section 5.1, though the bibliometric evidence reviewed here suggests this dynamic remains undertheorized in the trade technology literature. The subsequent acceleration through 2024-2025 with a 58.6% surge in annual output suggests the field has entered a self-reinforcing growth phase characteristic of emerging research

programmes, driven by expanding funding streams, new dedicated venues, and increasing cross-disciplinary fertilisation from artificial intelligence, logistics, and security studies. This trajectory warrants continued monitoring, as sustained growth rates of this magnitude are historically associated with imminent paradigmatic consolidation or, conversely, with premature fragmentation if integrative frameworks fail to emerge.

Disciplinary Dispersion and the Absence of Paradigmatic Authority

The extreme dispersal of publications across journals—with the leading outlet (*Journal of World Trade*) accounting for only 4.2% of the corpus and the top ten journals collectively representing a mere 16.2%—is a hallmark of pre-paradigmatic research fields, where no single disciplinary community has yet established the institutional authority to define the field's canonical questions, methods, or theoretical vocabulary (Kuhn, 1962). The tripartite clustering of journals across trade law and policy, mainstream economics, and technology and sustainability studies reflects three distinct entry points through which scholars have arrived at the same object of inquiry from divergent disciplinary starting points. This structural pluralism has both productive and limiting consequences. On one hand, it enriches the field with methodological diversity and prevents premature closure around a single analytical framework. On the other, it generates significant redundancy, hinders cumulative knowledge-building, and makes systematic literature synthesis methodologically complex. The prominence of the *Journal of World Trade* as the leading venue signals that legal and regulatory framing has historically provided the most coherent disciplinary home for this intersection—a finding that resonates with the political and governance

dimensions identified in Section 5.1, where questions of digital sovereignty, interoperability, and multilateral norm-setting are identified as pressing research frontiers. The interdisciplinary gaps documented in Section 5.4 similarly reflect this structural dispersion: the absence of integrative frameworks bridging law, ethics, computer science, and environmental science is not only a thematic gap but a direct consequence of the field's fragmented publication ecology.

Geopolitical Asymmetry and the Digital Divide in Knowledge Production

The geographic concentration of output reveals a structural asymmetry in knowledge production that mirrors, and in some respects amplifies, the broader inequalities of the global research system. China's dominance (40.6% of total contributions and 26.2% of corresponding authorships) is not merely a reflection of research capacity but of deliberate state strategy: sustained investments in customs digitisation, Belt and Road digital infrastructure, and the ambition to set global standards for digital trade have generated both the institutional incentives and the funding mechanisms to sustain high-volume output. However, the comparatively low Multi-Country Publication (MCP) rate of Chinese-led research (17.7%) suggests an inward orientation that limits the international uptake and generalisability of these contributions. The contrasting pattern among European contributors (Germany (MCP=50.0%) and the United Kingdom (MCP=40.9%)) reflects the structurally open research ecosystem fostered by multilateral funding frameworks such as Horizon Europe. India's 0% MCP rate is particularly consequential: as one of the world's most trade-exposed economies, its research community's insularity from international scholarly networks risks producing knowledge

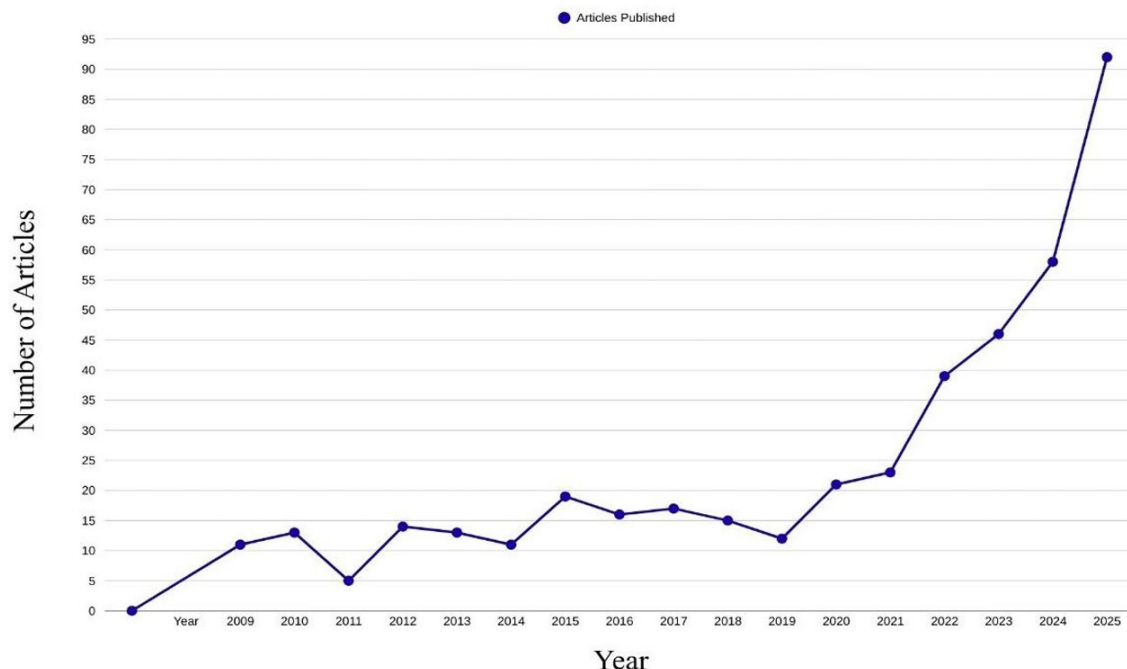


Figure 2: The distribution of international trade and border technologies publications by year.

Table 3: The most cited and influential publications in International Trade and Border Technologies.

Paper	Title	Total Citations (TC)	TC per Year	Noramalized TC
(Feng <i>et al.</i> , 2013)	Outsourcing CO ₂ within China	565	40,36	8,76
(Chang <i>et al.</i> , 2020)	Blockchain in global supply chains and cross border trade: a critical synthesis of the state-of-the-art, challenges and opportunities.	393	56,14	11,31
(Graaf <i>et al.</i> , 2020)	The new oil? The geopolitics and international governance of hydrogen.	216	30,86	6,21
(Manova and Yu, 2016)	How firms export: Processing vs. ordinary trade with financial frictions.	172	15,64	4,66
(Picci, 2010)	The internationalization of inventive activity: A gravity model using patent data.	150	8,82	3,58
(Jafari-sadeghi <i>et al.</i> , 2022)	Towards agility in international high-tech SMEs: Exploring key drivers and main outcomes of dynamic capabilities.	137	27,40	10,22
(Nahm, 2014)	Scale-up Nation: China's Specialization in Innovative Manufacturing.	135	10,38	6,32

Source: Author's work based on Scopus and WoS Databases.

disconnected from global best practices and comparative analytical frameworks. Most critically, the near-total absence of contributions from Africa, Latin America, the Middle East, and most of Southeast Asia constitutes a structural gap with direct implications for the social and equity dimensions developed in Section 5.2: the populations most affected by asymmetric border technology deployment-facing digital divides in trade participation, AI-driven migration management, and surveillance-intensive border regimes are precisely those least represented in the scholarly conversation shaping the governance of these systems. This epistemic exclusion is a structural feature of the current knowledge landscape, as evidenced by the bibliometric data, and addressing it is a prerequisite for producing research findings that are globally applicable and policy-relevant across different development contexts.

Intellectual Foundations and the Citation Gap

The citation landscape reveals a foundational paradox: the field's most influential works are not, in the main, about border technologies. The pre-eminence of (Feng *et al.*, 2013) focused on carbon-embodied trade flows reflects the intellectual gravitational pull of environmental economics and complex systems science on a field that has yet to develop an equivalent body of canonical work centred on border systems themselves. Similarly, the high normalised impact of (Chang *et al.*, 2020) captures the pandemic-driven reorientation toward supply chain resilience rather than toward border governance per se. This pattern of citation displacement where the most-cited works

address adjacent but distinct research questions is diagnostic of a field whose practitioners draw on intellectual resources from neighbouring domains in the absence of an indigenous theoretical core. Critically, the citation record's notable silence on key border-related technologies, such as border enforcement systems, customs automation, biometrics, predictive analytics, and digital sovereignty-reveals a significant disconnect between the field's current empirical foundations and the pressing political and social stakes. As highlighted in Sections 5.1 and 5.2, the deployment of AI-based tracking and biometric surveillance at borders represents an undertheorised frontier. Issues of governance, human rights, democratic accountability, and the risks of digital authoritarianism remain largely absent from the field's most influential literature. This gap underscores the urgent need for future empirical and interdisciplinary research to address these critical dimensions.

Conceptual Architecture and the Lexical Deficit

The keyword co-occurrence network provides the most structurally revealing evidence of the field's current condition. The bifurcation into two clusters one oriented toward digital trade infrastructure (cross-border e-commerce, blockchain, AI, logistics) and one toward macroeconomic trade determinants (technology, innovation, FDI, productivity, gravity model) encodes in network form the same disciplinary pluralism identified in the journal analysis. The exceptional bridging centrality of 'international trade' (betweenness=304.09) confirms that this term functions less as a substantive theoretical

concept than as a discursive connector the minimal common denominator through which scholars from divergent traditions anchor their work to a shared field identity. More revealing still is the near-absence from the network of terms that would be expected to constitute the core vocabulary of border technology research: 'customs automation', 'smart borders', 'biometrics', 'surveillance', 'border governance', or 'digital sovereignty' appear either peripherally or not at all. This lexical deficit is not merely a terminological curiosity; it indicates that the field has not yet developed the specialised conceptual vocabulary necessary to distinguish its object of inquiry from adjacent domains. In the sociology of scientific knowledge, the stabilisation of a field's lexicon is a key marker of paradigmatic consolidation; its absence here suggests that border technologies in international trade remain, as yet, a research theme rather than a research field. The invisibility of terms such as 'gender', 'human rights', 'equity', or 'authoritarianism' in the network is a bibliometrically observable finding: these concepts do not appear among the field's most co-occurring keywords, indicating that scholarship has yet to systematically engage with the social and political dimensions of border technology deployment. This lexical absence constitutes an empirically grounded research gap rather than a normative claim, and future research must address it if the field is to develop a more comprehensive analytical framework for border technology governance.

Synthesis: Towards an Integrated Research Agenda

Taken together, the five dimensions of analysis converge on a diagnosis of productive precarity: a field that is growing rapidly, attracting diverse disciplinary attention, and generating empirically rich contributions, but that has not yet achieved the

conceptual integration, geographic inclusivity, or lexical specificity characteristic of a mature research programme. Three structural priorities emerge clearly for future scholarship, each of which is elaborated through specific thematic directions in Section 5. First, theoretical consolidation: the field requires integrative frameworks capable of bridging the economic, technological, legal, and political dimensions of border technology governance moving beyond disciplinary silos toward a unified analytical vocabulary that can simultaneously accommodate supply chain economics, digital sovereignty, and human rights considerations. Second, geographic rebalancing: the systematic exclusion of the Global South both as knowledge producers and as subjects of comparative analysis impoverishes the field and undermines the policy relevance of its findings; addressing this deficit is not only a matter of scholarly inclusivity but a prerequisite for research that can speak to the equity and development implications developed in Section 5.2. Third, thematic deepening: the persistent displacement of border technologies by adjacent concerns signals the need for research that addresses border systems as primary objects of analysis examining their governance architectures, distributional consequences, and implications for trade equity, digital sovereignty, and democratic accountability. The present study, by systematically mapping the field's intellectual landscape, provides the empirical foundation for this agenda and offers a reference framework for scholars, institutions, and funding bodies seeking to invest in this increasingly consequential domain.

Implications and Emerging Research Areas

This section explores the multifaceted implications of the research while highlighting emerging research opportunities.



Figure 3: The most relevant Journals in International Trade and Border technologies.

in high-stakes environments. Furthermore, exploring public trust in automated border systems, especially in multicultural or conflict-prone regions, contributes to emerging debates on surveillance, data governance, and algorithmic accountability.

Finally, the gendered impacts of border technologies remain largely invisible in current discourse; this agenda foregrounds how these systems affect women's mobility, employment, and entrepreneurial access in trade-related contexts. Collectively, these directions offer a timely and original contribution to digital transformation studies, migration governance, and inclusive innovation, with strong potential for comparative, policy-relevant, and methodologically innovative research.

In sum, it would be worth studying how disparities in access to border technologies between developed and developing nations affect trade participation, labor mobility, and economic inclusion. Also, to assess the social consequences of using AI and IoT for migration management at borders, including ethical concerns, human rights, and refugee treatment. Moreover, explore societal perceptions of automated border systems, data privacy, and surveillance, especially in multicultural or conflict-prone regions. It could be interesting to investigate how border technologies impact gender equity in trade-related employment, mobility, and entrepreneurship.

Economic Implications

As border technologies become increasingly embedded in global trade infrastructures, their economic implications call for rigorous, forward-looking analysis. This research agenda offers a novel contribution by linking digital innovation with trade system resilience, financial inclusion, and climate-aligned policy. First, the integration of artificial intelligence into customs and logistics presents new opportunities to reduce transaction costs, enhance supply chain transparency, and optimize trade flows, particularly in low-collaboration or fragmented economies where inefficiencies persist. Second, the convergence of carbon pricing mechanisms with border technologies opens a promising frontier for emissions tracking and carbon accounting in international trade, with potential to inform green tariff regimes and accelerate climate-aligned trade governance. Third, the rise of blockchain-enabled trade finance, including decentralized finance and smart contracts, invites fresh inquiry into how these tools reshape cross-border transactions for SMEs and emerging markets, potentially lowering entry barriers and enhancing liquidity. Finally, the role of border technologies in buffering trade networks against systemic shocks (pandemics, geopolitical conflicts, or cyberattacks) demands new economic modeling approaches that capture adaptive capacity and interdependence. Collectively, these directions advance a multidisciplinary understanding of how border tech can serve not only as a facilitator of commerce but as a strategic lever for economic resilience, sustainability, and inclusive growth.

In sum, research should focus on the economic implications of the intersection of international trade and border technologies by examining how artificial intelligence can streamline customs, reduce transaction costs, and enhance supply chain transparency, especially in low-collaboration economies. Also, exploring how border technologies can support carbon accounting and emissions tracking in international trade, potentially influencing carbon tariffs and green trade policies. Furthermore, analyzing the economic impact of Decentralized Finance (DeFi) and smart contracts in cross-border transactions, especially for SMEs and emerging markets. Finally, related to the resilience of trade networks in crisis, it should be further investigated how border technologies can buffer trade systems against global disruptions (e.g., pandemics, wars, cyberattacks), and what economic models best capture this resilience.

Interdisciplinary Gaps Worth Exploring

The evolving landscape of border technologies presents an urgent need for integrative research that transcends disciplinary silos. This agenda introduces novel intersections between law, ethics, and computer science to develop robust frameworks for the responsible use of AI in border control and trade facilitation, an area where normative governance often lags behind technical deployment. It also advances the design of sustainable border infrastructures by combining environmental science, engineering, and economics to minimize ecological footprints while enhancing trade efficiency, offering a fresh contribution to green logistics and infrastructure planning. Equally innovative is the exploration of cultural transformations induced by digital borders, where anthropology and technology studies converge to illuminate how automated systems reshape cultural identities, trade rituals, and transnational relationships. Together, these directions reposition border technologies as not only technical artifacts but as complex socio-environmental systems, opening new pathways for interdisciplinary research and policy innovation.

CONCLUSION

In sum, this research advances a multidimensional understanding of border technologies by situating them within the broader political, social, and economic transformations shaping global trade. By moving beyond technical functionality to interrogate governance models, equity concerns, and sustainability imperatives, the study fills a critical gap in existing literature and offers a fresh lens on digital infrastructure as a site of power and policy. Its bibliometric approach not only maps the evolution of scholarly discourse but also identifies emerging intersections and neglected themes that warrant deeper interdisciplinary engagement. As nations confront climate imperatives, digital vulnerabilities, and shifting geopolitical alliances, this work provides timely insights for scholars, policymakers, and technologists seeking to navigate the complexities of trade in an era of accelerated technological convergence.

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ABBREVIATIONS

AI: Artificial Intelligence; **IoT:** Internet of Things; **CAGR:** Compound Annual Growth Rate; **WoS:** Web of Science; **JEL:** Journal of Economic Literature; **SMEs:** Small and Medium-sized Enterprises; **FDI:** Foreign Direct Investment; **CO₂:** Carbon Dioxide; **WTO:** World Trade Organization; **MCP:** Multi-Country Publication; **SCP:** Single Country Publication; **TC:** Total Citations; **EU:** European Union; **ASEAN:** Association of Southeast Asian Nations; **BRICS:** Brazil, Russia, India, China, and South Africa; **DEGEIT:** Department of Economics, Management, Industrial Engineering and Tourism; **R&D:** Research and Development; **DeFi:** Decentralized Finance.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

JEL CLASSIFICATION

F10, F13, O33, C89.

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Appendix 1: Co-occurrence Network.

Node	Cluster	Betweenness	Closeness	PageRank
International trade	1	304,091	0,017	0,083
Cross-border	1	10,727	0,012	0,029
Blockchain	1	2,866	0,011	0,016
Electronic commerce	1	3,989	0,011	0,025
Cross-border e-commerce	1	20,144	0,012	0,025
E-commerce	1	0,401	0,01	0,01
Internet	1	10,309	0,012	0,018
Artificial intelligence	1	0,19	0,011	0,009
Digital trade	1	1,155	0,011	0,009
Carbon leakage	1	0	0,01	0,006
Efficiency	1	0,52	0,011	0,01
Security	1	0	0,01	0,005
Block-chain	1	0,127	0,01	0,011
E-commerce	1	0,571	0,01	0,016
Information	1	1,483	0,011	0,011
Logistics	1	0,16	0,01	0,007
Trade	2	185,454	0,016	0,074
Technology	2	196,955	0,017	0,074
Innovation	2	46,474	0,014	0,045
International-trade	2	95,708	0,015	0,053
China	2	12,195	0,013	0,024
Impact	2	21,306	0,013	0,032
Productivity	2	8,586	0,013	0,034
Competition	2	3,539	0,012	0,018
Performance	2	7,665	0,013	0,023
Foreign Direct Investment	2	3,526	0,011	0,024
FDI	2	4,183	0,012	0,027
Market	2	2,56	0,011	0,018
Foreign direct investment	2	1,945	0,012	0,019
Policy	2	3,694	0,012	0,018
Globalization	2	0,535	0,011	0,011
Growth	2	4,099	0,012	0,019
Exports	2	0,768	0,011	0,013
Firms	2	1,511	0,012	0,02
Model	2	0,025	0,011	0,01
research-and-development	2	1,955	0,011	0,017
Economic-growth	2	2,107	0,012	0,017
Investment	2	0,968	0,011	0,013
Competitiveness	2	0,179	0,011	0,009
Determinants	2	0,614	0,011	0,013
Management	2	0,139	0,011	0,008
Export	2	0,114	0,011	0,011

Node	Cluster	Betweenness	Closeness	PageRank
WTO	2	0	0,009	0,004
CO ₂ emissions	2	0,886	0,011	0,011
Countries	2	0,056	0,011	0,01
Economics	2	1,063	0,011	0,009
Governance	2	0,149	0,01	0,008
Gravity model	2	1,795	0,011	0,01
Industry	2	1,298	0,011	0,01
Trade facilitation	2	0,222	0,01	0,006

Source: Biblioshiny based on Scopus and WoS databases.