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ORIGINAL

Technological Innovation in Ship Collision Avoidance: A Bibliometric Analysis of Recent Developments and Trends

Innovación tecnológica en la prevención de colisiones de buques: un análisis bibliométrico de desarrollos y tendencias recientes

Albertha Lolo Tandung[1], Nenny[1], Darmawan Napitupulu[2]

[1]Politeknik Pelayaran Barombong. Makassar, Indonesia.
[2]Research Center for Domestic Government, National Research and Innovation Agency.

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Corresponding Author: Darmawan Napitupulu

ABSTRACT

This study provides a comprehensive bibliometric analysis of global research on ship collisions, mapping publication trends, key contributors, and primary themes within the field. This study distinguishes itself by offering the first in-depth bibliometric examination of ship collision avoidance research trends using comprehensive Scopus data, filling a gap in understanding how this field has evolved across disciplines and identifying emerging areas for future study. Total 381 relevant articles were analyzed to understand the evolution and current landscape of ship collision research. The results highlight a notable growth in publications since the early 2000s, driven by increasing concerns over maritime safety and the economic and environmental impacts of collisions. Key authors and countries, especially China, emerge as major contributors to the field, advancing topics such as autonomous technology integration, numerical simulations for safety, and structural resilience in collision scenarios. Three primary research themes were identified: the integration of COLREGs and autonomous technology for collision avoidance, maritime safety enhancement through numerical simulation, and structural crashworthiness and risk assessment. This research lays the groundwork for further exploration of ship collision prevention and maritime safety advancements. Finally, the suggestions on future research are also made.

Keywords: Ship Collision; Bibliometric Analysis; Publish or Perish; Bibliomagika; VOSviewer.

RESUMEN

Este estudio proporciona un análisis bibliométrico exhaustivo de la investigación global sobre colisiones de buques, mapeando las tendencias de publicación, los principales contribuyentes y los temas principales dentro del campo. Este estudio se distingue por ofrecer el primer examen bibliométrico profundo de las tendencias de investigación en prevención de colisiones de buques utilizando datos exhaustivos de Scopus, llenando un vacío en la comprensión de cómo este campo ha evolucionado a través de las disciplinas e identificando áreas emergentes para futuros estudios. Se analizaron un total de 381 artículos relevantes para comprender la evolución y el panorama actual de la investigación sobre colisiones de buques. Los resultados destacan un crecimiento notable en las publicaciones desde principios de la década de 2000, impulsado por la creciente preocupación por la seguridad marítima y los impactos económicos y ambientales de las colisiones. Autores y países clave, especialmente China, emergen como importantes contribuyentes al campo, avanzando en temas como la integración de tecnología autónoma, simulaciones numéricas para la seguridad y resiliencia estructural en escenarios de colisión. Se identificaron tres temas de investigación principales: la integración de COLREG y tecnología autónoma para la prevención de colisiones, la mejora de la seguridad

marítima mediante simulación numérica, y la resistencia estructural a impactos y la evaluación de riesgos. Esta investigación sienta las bases para una mayor exploración de la prevención de colisiones de buques y los avances en seguridad marítima. Finalmente, se formulan sugerencias para futuras investigaciones.

Palabras clave: Colisión de Barcos; Análisis Bibliométrico; Publicar o Perecer; Bibliomagika; VOSviewer.

INTRODUCTION

The rapid growth of the maritime industry has brought both economic benefits and increased safety risks, particularly concerning ship collisions, which remain a significant threat to maritime safety and environmental preservation.[1] As global trade intensifies, the density of vessel traffic has increased, especially in congested routes and narrow waterways, raising the likelihood of collisions. These incidents not only endanger human lives and marine ecosystems but also have considerable economic implications, from costly repairs to potential legal liabilities. Consequently, ship collision prevention and risk mitigation have become top priorities within the industry and for regulatory bodies worldwide.

The urgency to address these issues has driven substantial research efforts into understanding the factors contributing to ship collisions and developing technologies to prevent them. Traditional methods, such as compliance with the International Regulations for Preventing Collisions at Sea (COLREGs), have been supplemented by emerging technologies, including artificial intelligence (AI), autonomous navigation systems, and advanced risk assessment models. Despite this progress, the field remains fragmented, with studies often focused on isolated aspects, such as specific technologies or individual risk factors, lacking a comprehensive overview that captures global trends, collaborative networks, and thematic development within ship collision research.

Although several studies have examined safety aspects and collision avoidance technology for ships, including advanced algorithms and artificial intelligence (AI) for autonomous ship control, these studies still reveal gaps in the literature. For instance, the study "Intelligent Ship Collision Avoidance in Maritime Field" highlights advances in collision avoidance technology with AI but focuses primarily on algorithms and collaboration among research institutions,[2] without fully addressing integration with COLREG navigation rules in hybrid encounters between autonomous and traditional ships. Similarly, the study "Individual Collision Risk Assessment in Ship Navigation" emphasizes individual collision risk assessment and parameter analysis,[3] but lacks comprehensive integration of risk parameters in multi-ship or dynamic environmental scenarios. The research on "The Application of Reinforcement Learning (RL) in Autonomous Ship and Collision Avoidance" identifies challenges in training RL models for autonomous ships, particularly in parameter selection and model resilience in complex scenarios.[4] The gap across these studies is that they focus on specific technologies without providing a comprehensive analysis of global trends in ship collision research. This paper fills that gap by offering a complete bibliometric analysis based on Scopus Publications that unifies key themes in the field, providing a foundation for a holistic understanding and guiding future research directions in maritime safety.

Our study seeks to fill this gap by offering the first in-depth examination of global trends in ship collision, distinguishing itself from previous research by utilizing the Scopus database. Through bibliometric analysis and content analysis, these studies provide valuable insights into how ship collision publications has evolved across different disciplines and inform future research directions. This study aims to describe 1) how the performance of ship collision publications is based on authors, papers, sources, affiliations, and countries, 2) what the main prevalent themes of ship collision publications between scholars are, and 3) what the future research direction is related to ship collision.

METHOD

This is an observational, descriptive bibliometric study conducted at Politeknik Pelayaran Barombong in October 2024. The unit of analysis is scientific output on ship collision/collision avoidance indexed in Scopus from 1978 to 2024.The bibliometric approach is particularly useful as it offers a quantitative assessment of research performance, serving as an objective indicator of academic interest and influence in ship collision studies.

Methods like citation analysis and co-occurrence mapping were utilized to systematically map out publication networks and reveal trends. Citation analysis reveals the significance of particular articles, authors, and journals, while co-occurrence mapping highlights emerging topics and potential future research paths based on authors' keywords. Together, these techniques reduce researcher bias and provide a clear overview of the research landscape.[5]

Data Collection

The bibliometric analysis was conducted as of October 5, 2024. We used the Scopus database due to its extensive range of citations and abstracts across fields like STEM (Science, Technology, Engineering, and Mathematics).[6,7] This database offers a broad overview of global scientific research output and is widely

recognized in the scientific community as a core source of research data.[8] Scopus is highly regarded for its rigorous indexing standards, ensuring that only high-quality, peer-reviewed journals are included, which adds credibility to our research. Scopus has frequently been utilized in bibliometric studies.[6,9,10] Due to its reliability, scope, and frequent use in bibliometric studies, Scopus is widely considered a cornerstone resource by the international scientific community, reinforcing our decision to use it as the sole database for this analysis.

We employed a keyword-based search strategy rooted in our research questions to locate relevant documents on ship collisions. The TITLE field in Scopus was specifically used because it allows for a more focused retrieval of documents directly addressing our topic, reducing the inclusion of unrelated studies that might appear if broader fields were used. The keywords used were "ship collision" and "ship collisions." Boolean operators using "OR" were applied to include synonymous variations of the term, and quotation marks were used to ensure exact phrase matching. The final search string was: TITLE ("ship collision" OR "ship collisions").

The initial search in Scopus retrieved 847 records, after which database filters—peer-reviewed journal articles, English language, and final publication stage—were applied, excluding 466 records and leaving 381. These parameters functioned as search limitations rather than thematic exclusion criteria. The inclusion criterion was that studies explicitly addressed ship collision or collision avoidance, as determined from the title, abstract, and keywords, while the thematic exclusion criterion was the absence of relevance to ship collision topics. Given that the search used the TITLE field, all remaining records already met the thematic criterion, so no additional exclusions were necessary at the exit screening stage. Therefore, the thematic screening of titles, abstracts, and keywords confirmed that all 381 articles were relevant and were subsequently included in the bibliometric and content analysis. Figure 1 presents the search, database filtering, and thematic screening workflow with counts at each stage.

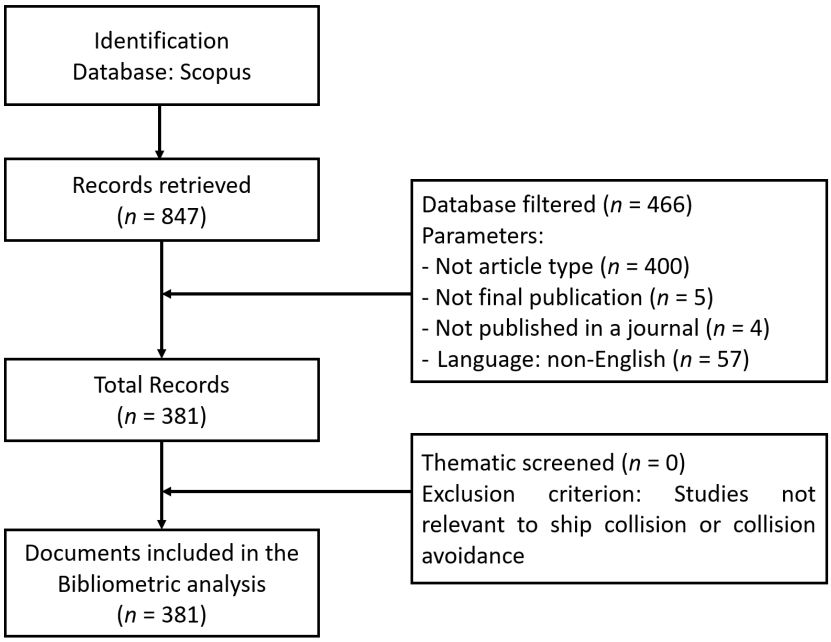

Figure 1. The Stages of Data Filtering

Data Analysis

All bibliographic records and metadata were downloaded from Scopus in .csv format for processing in external tools such as VOSviewer. No analyses were performed inside the Scopus interface. The study analyzed scientific outputs on ship collision and avoidance using bibliometric data from Scopus. The variables examined included total publications and citations, along with authors, countries, affiliations, source titles, and keywords used to form thematic clusters. Before beginning our analysis, we undertook data cleaning and harmonization, crucial steps in bibliometric analysis to ensure data accuracy and reliability,[11] with particular focus on keywords. Utilizing the Thesaurus function in VOSviewer, we refined keywords to address inconsistencies within the dataset, an essential step for accurate co-occurrence analysis. The process began by downloading the Scopus data in .csv format, selecting the relevant files, and carefully editing key columns using clustering functions to group similar terms. The Thesaurus function proved especially useful for standardizing keywords, enabling us to maintain consistency and accuracy across a wide range of research outputs, thereby ensuring a solid foundation for analyzing co-occurrence patterns and trends in subsequent stages.

Subsequently, all bibliometric mapping and citation analyses were conducted using VOSviewer version 1.6.20. For the keyword co-occurrence analysis, we examined the author keywords field using the full counting method and set the minimum occurrence threshold at four (≥4) as parameters, consistent with the mapped set

reported in the results. We also applied VOSviewer's clustering settings to produce both network and overlay visualizations. In conducting the citation analysis, the units of analysis included documents, authors, and countries, with the full counting method employed to ensure consistency in measurement. All workflow steps and parameter configurations were systematically documented to facilitate transparency and reproducibility of the analysis.

RESULTS

Publication Trends

Table 1. Publication and Citation by Year

Year	TP	TC
1978	1	11
1981	1	2
1982	2	129
1983	2	63
1985	3	11
1986	1	31
1987	3	77
1989	5	56
1991	1	1
1992	1	3
1993	2	1
1994	4	142
1996	1	94
1998	1	191
1999	1	8
2000	2	76
2002	2	45
2003	3	84
2005	1	2
2006	3	35
2007	5	326
2008	6	492
2009	4	150
2010	7	427
2011	5	323
2012	7	293
2013	8	582
2014	12	633
2015	11	815
2016	18	1039
2017	22	929
2018	14	346
2019	28	866
2020	35	1072
2021	33	1017
2022	42	682
2023	48	524
2024	36	45
Total	381	11623

Note: TP=total number of publications; TC=total citations

The bibliometric analysis of publication and citation trends on the topic of ship collisions reveals a notable growth in research interest, especially since the early 2000s, with the number of annual publications reaching its peak in recent years. This trend, as seen in table 1, underscores growing awareness of maritime safety and the environmental and economic impacts of ship collisions. Although early years saw only a few publications, certain studies from this period, such as those in 1994 and 1998, accumulated significant citations, indicating foundational contributions that remain influential. The year 2020 saw the highest number of citations, highlighting influential contributions. Recent years show an unprecedented volume of publications, though the citation impact per article has slightly decreased, likely due to the time needed for newer research to garner citations. Overall, this trend underscores a sustained and growing academic interest in ship collision research, with recent work contributing to an expanding body of knowledge.

Most Productive and Influential Authors

The bibliometric analysis highlights the most influential and productive authors in ship collision research, as summarized in table 2. Kujala from Tallinn University of Technology emerges as the most influential author in ship collision research, with the highest citation count (1250) across 10 publications, reflecting significant impact. Goerlandt from Dalhousie University follows closely, with 1178 citations for 9 papers. Amdahl from the Norwegian University of Science and Technology is the most productive, with 13 publications and 617 citations, showing consistent contribution. Interestingly, China has a noticeable presence with multiple contributing authors (Paik, Zhang, and Weng), indicating that China is expanding its research efforts in maritime safety and ship collision, likely driven by its significant role in global shipping and maritime activities.

Table 2. Top 10 Authors with at least 7 Publications

Full Name	Current Affiliation	Country	TP	TC
Amdahl, J.	Norges Teknisk-Naturvitenskapelige Universitet	Norway	13	617
Kujala, P.	Tallinna Tehnikaülikool	Estonia	10	1250
Goerlandt, F.	Dalhousie University	Canada	9	1178
Guedes Soares, C.	Instituto Superior Técnico	Portugal	9	428
Paik, J.K.	Harbin Engineering University	China	9	437
Pedersen, P.T.	Technical University of Denmark	Denmark	9	535
Zhang, J.	Wuhan University of Technology	China	9	324
Weng, J.	Shanghai Maritime University	China	8	247
van Gelder, P.H.A.J.M.	TU Delft	Netherlands	8	484
Chai, T.	Jimei University	China	7	146

Note: TP=total number of publications; TC=total citations

Most Productive and Influential Countries

The bibliometric analysis, as seen in table 3, shows that China leads global research on ship collisions with the highest number of publications (177) and citations (3,359), indicating both productivity and impact as illustrated in table 3. South Korea and the United Kingdom follow, contributing significantly in both output and influence. Finland, though producing fewer studies, has a high citation count (1,931), highlighting the strong impact of its research.

Table 3. Top 10 Countries with at least 12 Publications

Country	Continent	TP	TC	TLS
China	Asia	177	3359	66
South Korea	Asia	40	1018	13
United Kingdom	Europe	34	1215	40
Finland	Europe	24	1931	20
United States	North America	21	781	26
Norway	Europe	20	1010	9
Portugal	Europe	15	931	16
Denmark	Europe	13	668	10
Netherlands	Europe	13	643	10
Japan	Asia	12	329	3

Note: TP=total number of publications; TC=total citations; TLS=total link strength

Figure 2 illustrates the international collaborative network in the field of ship collision research. China has the largest cirlce, indicating it is the main contributor to research on ship collision. The analysis employs total link strength (TLS) as the primary metric of collaborative intensity. For each country node, TLS represents the cumulative strength of all co-authorship links connecting that country with others in the network, thereby reflecting both the breadth and depth of its international research partnerships. The results indicate that China demonstrates the highest level of collaboration (TLS = 66), followed by the United Kingdom (TLS = 40), the United States (TLS = 26), and Finland (TLS = 20) as presented in table 3. These results indicate complementary roles within the network: China as a prolific, highly collaborative hub; the United Kingdom and the United States as trans-regional connectors; and Finland as a source of high-impact, selectively collaborative work.

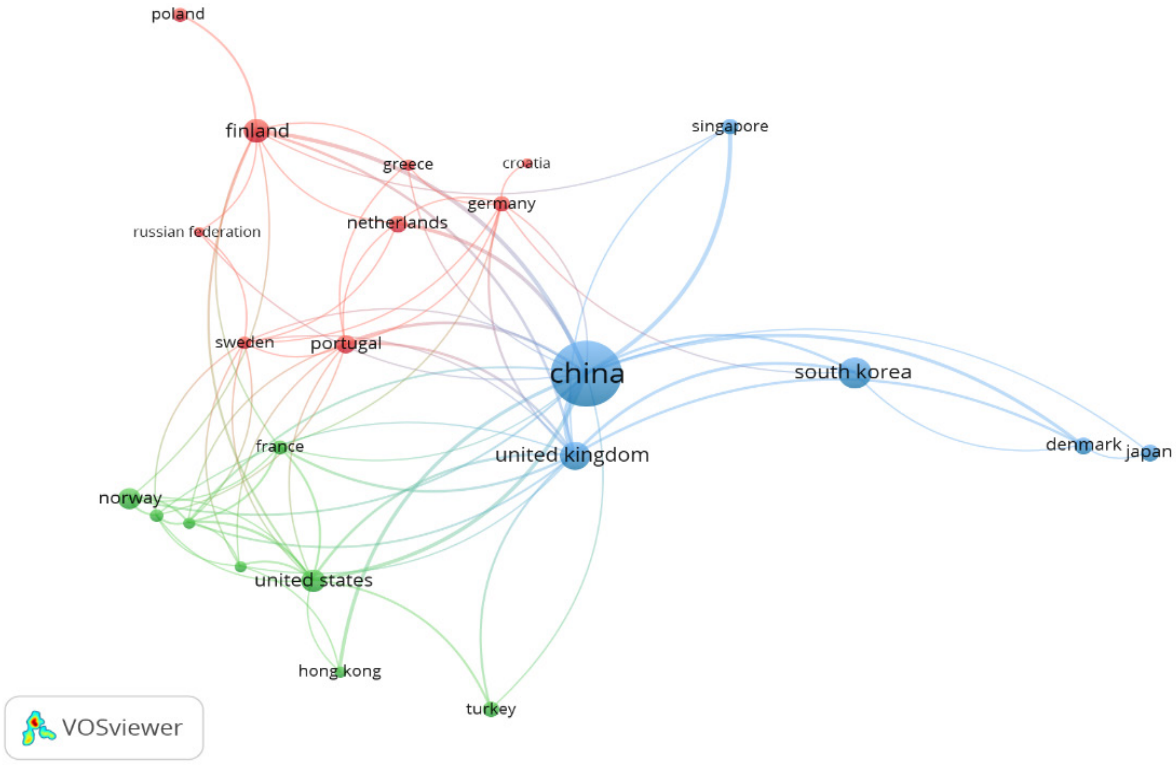

Figure 2. Countries' Collaboration Network

Most Active Source Titles

Table 4 indicates that top-tier (Q1) journals dominate the research on ship collision, with Ocean Engineering leading in both productivity (78 publications) and influence (3200 citations). Other Q1 journals, like Marine Structures and Reliability Engineering and System Safety, also show high citation counts, reinforcing their impact. In comparison, Q2 journals such as Journal of Marine Science and Engineering contribute meaningfully but with a slightly lower impact, reflecting a secondary role in this research area. Overall, Q1 sources are key drivers in advancing ship collision studies.

Table 4. Most Active source titles with at least 6 publications

Source Title	Publisher	TP	TC	Quartile
Ocean Engineering	Elsevier	78	3200	Q1
Marine Structures	Elsevier	26	1332	Q1
Journal of Marine Science and Engineering	MDPI	25	360	Q2
Ships and Offshore Structures	Taylor and Francis	15	578	Q2
Journal of Navigation	Cambridge University Press	13	903	Q2
Reliability Engineering and System Safety	Elsevier	13	871	Q1
Safety Science	Elsevier	7	782	Q1
IEEE Access	IEEE	6	53	Q1
Journal of Ship Research	Society of Naval Architects and Marine Engineers	6	225	Q2

Note: TP=total number of publications; TC=total citations

Highly Cited Documents

The bibliometric analysis of top 10 highly cited papers on ship collision topics reveals that many of the top-cited papers are published in high-impact quartiles, reflecting their significant influence in the field (table 5). Notably, works focused on autonomous navigation[12] and marine traffic analysis using AIS data[13] have particularly high citation counts, indicating strong scholarly interest and relevance. The high citation per year (C/Y) rates in more recent studies, such as [14] and [15], suggest that cutting-edge approaches to collision avoidance and risk assessment—especially those utilizing simulation and advanced algorithms—are capturing the attention of researchers and practitioners. The top ten articles on ship collision cover a wide range of topics, including collision risk,[16,17,18] collision avoidance technologies,[12,14,15] and the use of AIS data for monitoring and detecting near misses in marine traffic.[13,16,19] Additionally, foundational work on the impact mechanics in ship collisions is highlighted in.[20]

Table 5. Top 10 highly cited papers

No.	Author(s)	Title	TC	C/Y
1	Statheros et al.[12]	Autonomous ship collision avoidance navigation concepts, technologies and techniques	314	1963
2	Silveira et al.[13]	Use of AIS data to characterise marine traffic patterns and ship collision risk off the coast of Portugal	291	2645
3	Qu X et al.[18]	Ship collision risk assessment for the Singapore Strait	266	2046
4	Johansen et al.[14]	Ship collision avoidance and COLREGS compliance using simulation-based control behavior selection with predictive hazard assessment	257	3213
5	Zhang W et al.[16]	A method for detecting possible near miss ship collisions from AIS data	224	2489
6	Goerlandt et al.[21]	A framework for risk analysis of maritime transportation systems: A case study for oil spill from tankers in a ship-ship collision	213	2367
7	Pedersen et al.[20]	On impact mechanics in ship collisions	191	735
8	Hänninen et al.[17]	Influences of variables on ship collision probability in a Bayesian belief network model	185	1542
9	Zhang W et al.[19]	An advanced method for detecting possible near miss ship collisions from AIS data	180	2250
10	Huang Y et al.[15]	Generalized velocity obstacle algorithm for preventing ship collisions at sea	172	3440

Note: TC = total citations; C/Y = total citations per year

The Most Frequent Keywords in Ship Collision Publications

Keywords describe an article's topic, central idea, or critical topic of a particular research field.[22] After cleaning, we had 1028 keywords; we combine 14 keywords which are inconsistent written but have the meaning such as "ais" and "automatic identification system (ais)", "ship collision", "ship collisions" and "ship-ship collisions" and keywords with a co-occurrence frequency below four. Thus, 29 keywords could be mapped, as seen in figures 3 and 4. The circles (nodes) represent specific keywords or topics, and the size of the circles (nodes) shows the number of co-occurrences, while the link size shows the number of networks.

Based on table 6, the ten keywords with the highest co-occurrence frequency are: ship collision (123), ship collision avoidance (36), ais (29), risk analysis & assessment (20), maritime safety (20), collision risk (15), colregs (15), ship domain (13), numerical simulation (10) and Bayesian network (9). These keywords are grouped into specific themes, or clusters based on their relatedness. Figure 3 shows three clusters of ship collision publications, each marked by red, green, and blue, dotted circles, representing different thematic areas within the research.

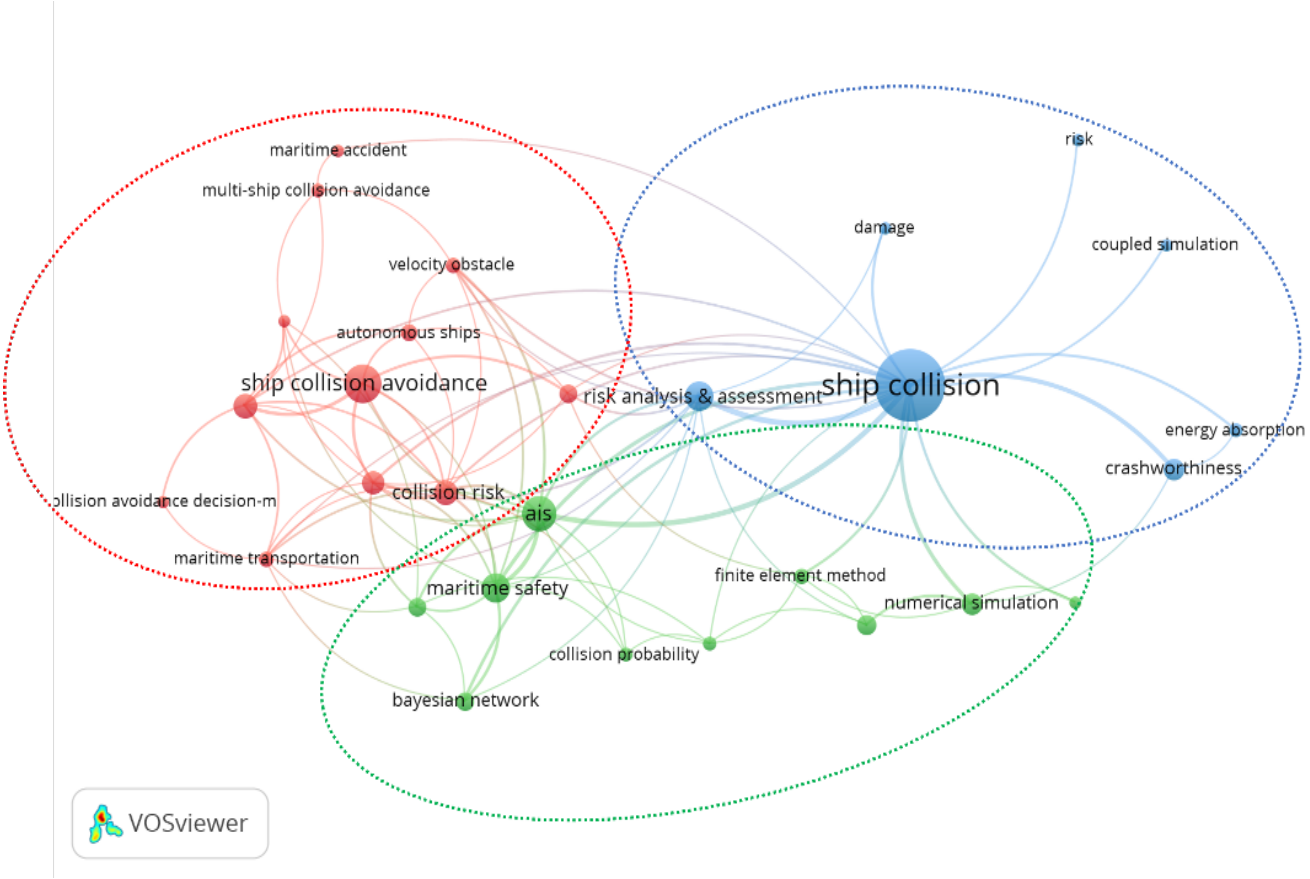

Figure 3. Thematic Cluster of Ship Collision Publications

The visualization overlay on the VOSviewer mapping results (figure 4) shows the publication trend of keywords based on the year of appearance. The lighter the color of the link and circle, the more recent the publication. Keywords from recent publications, such as ship collision risk, collision probability, impact force and autonomeous ships and are particularly notable.

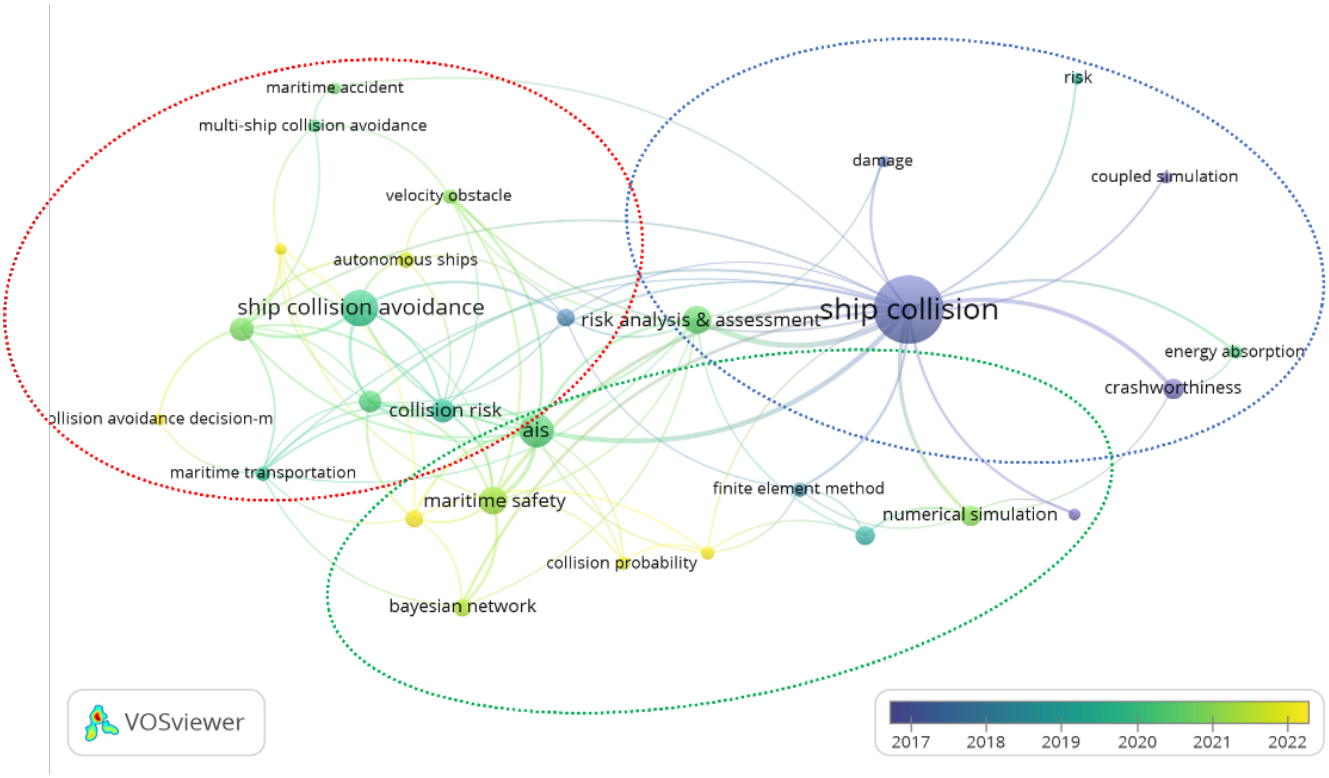

Figure 4. Trends of Ship Collision Publications by Year

Table 6. Top 10 highly cited papers

Cluster	Topic occurrences
Cluster 1	Ship collision avoidance (36), Collision risk (15), Colregs (15), Ship domain (13), Safety (8), Autonomous ships (7), Maritime transportation (6), Velocity obstacle (6), Multi-ship collision avoidance (5), collision avoidance decision-making (4), Ship maneuverability (4), Maritime accident (4)
Cluster 2	Ais (29), Maritime safety (20), Numerical simulation (12), Ship-bridge collision (10), Ship collision risk (9), Bayesian network (9), Collision probability (5), impact force (5), finite element method (5)
Cluster 3	Ship collision (123), Risk analysis & assessment (20), Crashworthiness (12), Energy absorption (5), Coupled simulation (4), Damage (4), Risk (4)

DISCUSSION

This study utilized bibliometric analysis to thoroughly examine the evolution, current state, and future research trajectories of ship collision publications. By analyzing an extensive collection of 381 papers, the study mapped the intellectual landscape of the field, influential contributors, dominant trends and highlighting key themes. This section aims to delve deeper into the findings, interpreting their implications for the field and outlining their relevance for future research directions. To achieve this, we addressed three main research questions, each analyzed according to different primary themes.

Ship Collision Publication Trends

Regarding the first question related to the trend of publications, our findings indicate that research on ship collisions has grown substantially, especially since the early 2000s, signaling increased attention to maritime safety and the environmental and economic impacts of collisions. Sustained by growing maritime traffic and an increase in collision incidents, research into effective collision avoidance systems and risk assessment models is on the rise. For example, previous studies explored methods for detecting near-miss ship collisions using Automatic Identification System (AIS) data.[16,17] Our findings also align with the trends observed in maritime safety research, as [23] similarly found that poor visibility conditions significantly increase the financial costs of collisions. This highlights the economic importance of maritime safety, a key factor driving the increased focus on studies related to collisions. Furthermore, research into technological solutions continues to advance, with studies exploring autonomous ship navigation systems for collision avoidance. These studies strategically incorporate advanced algorithms to improve decision-making in unsafe conditions. This shows a shift toward integrating artificial intelligence and real-time data analytics into maritime operations, a trend expected to significantly reduce collision occurrences.[24,25]

However, this growth is reflected not only in the increasing volume of publications but also in the significant contributions of leading researchers and countries across the globe. Notably, Kujala from Tallinn University of Technology emerges as one of the most influential authors, with high citation counts that reflect his impact on the field. One of Kujala's most highly cited articles, "Towards the Assessment of Potential Impact of Unmanned Vessels on Maritime Transportation Safety", analyzes 100 maritime accident reports using what-if analysis and HFACS-MA to evaluate the safety implications of unmanned vessels. The study finds that while autonomous ships may reduce navigational accidents such as collisions and groundings, the consequences of non-navigational accidents could be more severe compared to manned vessels.[26] This finding is consistent with the contribution of Statheros et al.[27] one of the most highly cited documents in the field of ship collision, which emphasizes the importance of developing path planning methods and collision avoidance systems based on artificial intelligence to ensure that autonomous ships can operate safely and in compliance with COLREGs.

Correspondingly, China leads globally in publication output, reflecting how its extensive shipping activities and strategic maritime interests have driven academic and policy-oriented research, positioning the country at the forefront of maritime studies. Moreover, its central position, with numerous connections to other countries, highlights its role as a hub of collaboration and reflects its strong research partnerships with many countries. This prominence can be explained by the fact that, as the world's largest exporter and the second-largest economy, China's maritime sector is a central pillar of its economic strategy, with the Belt and Road Initiative (BRI) further intensifying shipping activities and necessitating robust research to enhance infrastructure and efficiency.[28]

Thematic Cluster in Ship Collision Publications

The second research question regarding the most prevalent themes on ship collision research indicates three main research themes used based on cluster analysis by VOSviewer. Cluster 1, identified as the Integration of COLREGs and Autonomous Technology in Ship Collision Avoidance, highlights the intersection between emerging

technologies and established navigation rules. Research in this area focuses on developing autonomous algorithms that comply with COLREGs, supported by detection technologies and risk assessment systems that enable real-time hazard identification and improved compliance with maritime safety.[29,30] These advancements are crucial as maritime traffic intensifies and autonomous vessels increasingly operate in complex environments. Parallel efforts address maneuvering and control strategies tailored to dense traffic scenarios, with real-time decision-making systems and multi-ship simulations playing a central role in validating performance.[31,32] Enhancing vessel maneuverability not only strengthens operational efficiency but also mitigates safety risks, underscoring the importance of technological and regulatory adaptation as the maritime sector transitions toward greater automation.[33]

Cluster 2, labeled as Maritime Safety Based on Numerical Simulation, focuses on improving ship operation safety through technological and risk analysis methods. AIS data are widely used to identify traffic patterns and collision risks, while Bayesian networks and fuzzy cognitive maps support advanced accident probability estimation and safety management.[34,35] Numerical simulations provide valuable insights into hazardous maritime scenarios, enabling more informed decision-making in navigation risk assessment. In addition, impact force analysis and finite element methods are applied to assess structural vulnerabilities in collision situations, offering critical guidance for ship design and safety protocols.[36,37] Overall, this cluster integrates simulation, risk prediction, and structural analysis to enhance safety standards, reduce accident risks, and strengthen the sustainability and resilience of maritime operations.[38]

Cluster 3, labeled as Ship Collision Risk and Crashworthiness Analysis, focuses on assessing collision risks and improving structural resilience. Studies highlight the importance of analyzing safety in congested maritime areas, particularly the role of human and environmental factors in elevating collision probabilities, while innovations in lightweight structural design enhance crashworthiness without reducing efficiency.[39,40] Parallel research explores energy absorption and structural integrity, proposing reliability-based design methods (LRFD) to ensure hull strength under collision stresses.[41,42] Advances in real-time monitoring technologies further support safer vessel operations by generating critical data to inform both design improvements and operational strategies.[43,44]

Future Research Trend

Based on the identified research themes, future research directions on ship collision will likely converge on three intertwined fronts aligned with the clusters above. First, autonomy-oriented studies will prioritize COLREGs-compliant algorithms that operate under uncertainty and dense multi-ship interactions, supported by real-time detection and risk assessment and validated in high-fidelity, multi-ship simulation environments. Second, safety modeling will deepen the coupling of AIS-driven traffic analysis with probabilistic approaches (e.g., Bayesian networks, fuzzy cognitive maps) and numerical simulations (e.g., impact force modeling, finite element analysis) to improve prediction, scenario testing, and decision support, ideally within standardized benchmark scenarios and port/sea-lane "digital twins." Third, crashworthiness research will advance lightweight, energy-absorbing structures and reliability-based design (LRFD) while leveraging real-time monitoring data to close the loop between design, operation, and maintenance. Across these streams, integrative work on human factors, environmental conditions, and adaptive legal–regulatory frameworks will be essential, alongside field trials and hardware-in-the-loop validation to translate laboratory advances into robust, scalable maritime safety solutions.

Despite the outlined future directions, certain limitations of this study should be acknowledged. First, the analysis relies solely on data from the Scopus database, which, while comprehensive, may omit relevant publications indexed in other databases such as Web of Science or IEEE. This choice could limit the breadth of the findings and the generalizability of the research trends observed. Second, the focus on English-language publications excludes potentially valuable studies in other languages, particularly from countries with substantial maritime industries. Third, bibliometric analysis provides a quantitative view of the field but lacks in-depth qualitative insights into the methodologies and findings of individual studies, which are essential for a nuanced understanding of the research impact. Future studies could address these limitations by incorporating multiple databases, including non-English publications, and using qualitative methods alongside bibliometric analysis for a more holistic understanding of ship collision research.

CONCLUSIONS

This bibliometric analysis provides an in-depth examination of the global research landscape on ship collisions, highlighting key trends, influential contributors, and major thematic areas within the field. The analysis reveals a steady increase in research interest over recent years, underlining the growing academic and industry focus on maritime safety and the mitigation of ship collision risks. Key authors and countries, particularly China, have made significant contributions, driving advances in autonomous technology, numerical simulations, and structural analysis for collision resilience. The three main research themes identified—COLREGs integration

with autonomous technology, maritime safety through numerical simulation, and crashworthiness and risk assessment—reflect the evolving priorities in this area. Future research directions propose the enhancement of autonomous systems, advanced simulation incorporating environmental factors, and innovative ship design for improved collision resilience. This study underscores a collaborative global effort toward advancing ship collision research, setting a foundation for continued developments in maritime safety and risk management.

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AUTHORSHIP CONTRIBUTION

Conceptualization: Albertha Lolo Tandung, Nenny, Darmawan Napitupulu.
Data curation: Albertha Lolo Tandung, Nenny.
Formal analysis: Albertha Lolo Tandung, Darmawan Napitupulu.
Research: Albertha Lolo Tandung, Nenny.
Methodology: Albertha Lolo Tandung, Nenny, Darmawan Napitupulu.
Project management: Albertha Lolo Tandung, Nenny, Darmawan Napitupulu.
Resources: Albertha Lolo Tandung, Nenny, Darmawan Napitupulu.
Software: Albertha Lolo Tandung, Nenny, Darmawan Napitupulu.
Supervision: Albertha Lolo Tandung, Darmawan Napitupulu.
Validation: Albertha Lolo Tandung, Darmawan Napitupulu.
Display: Albertha Lolo Tandung, Nenny, Darmawan Napitupulu.
Drafting - original draft: Albertha Lolo Tandung, Nenny, Darmawan Napitupulu.
Writing - proofreading and editing: Albertha Lolo Tandung, Nenny, Darmawan Napitupulu.