International Journal of Innovation and Industrial Revolution IJIREV
EISSN: 2637-0972
Volume: 8 Issue: 24 (March 2026) PP. 80-95

INTERNATIONAL JOURNAL OF INNOVATION AND INDUSTRIAL REVOLUTION (IJIREV)
www.gaexcellence.com/ijirev

MAPPING THE KNOWLEDGE LANDSCAPE OF SUBMARINE CABLE INFRASTRUCTURE: A BIBLIOMETRIC ANALYSIS

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Article Info:

Article history:
Received date: 30.11.2026
Revised date: 14.12.2026
Accepted date: 28.01.2026
Published date: 01.03.2026

To cite this document:

Ghazali, M. H., Mad Kaidi, H., & Sarip, S. (2026). Mapping The Knowledge Landscape of Submarine Cable Infrastructure: A Bibliometric Analysis. *International Journal of Innovation and Industrial Revolution, 8* (24), 80-95.

Abstract:

Submarine cable infrastructure is crucial for global telecommunications, supporting international data transfer and internet connectivity. As the demand for high-capacity and resilient networks grows, the need for a comprehensive understanding of research trends and developments in this field becomes more important. However, a systematic review of the academic literature on submarine cable infrastructure remains scarce. This bibliometric review aims to address this gap by analyzing the evolution of research on submarine cables and their technological, economic, and regulatory aspects. Data was collected from Scopus using advanced search queries with the keywords "submarine," "cables," "fiber," and "fibre," yielding a final dataset of 1,989 documents. Statistical analysis and graph generation were conducted using Scopus Analyzer, while OpenRefine was utilized for data cleaning and harmonization. VOSviewer was then employed for data visualization to identify key research clusters, co-authorship patterns, and emerging trends. The analysis reveals a significant increase in research output over the past decade, with notable contributions from leading countries, including the United States, the United Kingdom, and China. Key thematic areas include advances in cable technology, network resilience, and the economic and regulatory challenges of deploying submarine cables. This bibliometric review offers valuable insights into the structure and dynamics of the field, highlighting key areas for future research and offering a foundational reference for stakeholders in the submarine cable industry.

International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
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DOI: 10.35631/IJIREV.824006

Keyword:

Cable Technology, Fiber, Fibre Submarine, Submarine Cables

Introduction

Submarine cables are a critical component of global communication and energy infrastructure, playing a pivotal role in international connectivity and the transition towards sustainable energy systems. These cables facilitate high-speed internet access, communication, and energy transmission, which are essential drivers of economic growth, innovation, and infrastructure development (Setianingrum et al., 2024). The increasing demand for internet services, driven by the proliferation of social media and cloud computing, underscores the importance of submarine cables in the modern digital economy(Aishwarya, 2020). This paper explores the revolutionary of submarine cable infrastructure, examining the technological advancements, economic considerations, and strategic implications of these underwater networks.

The significance of submarine cables in global communication cannot be overstated. They are the backbone of international data transmission, enabling seamless connectivity for telecom providers and content companies like Google, Facebook, and Microsoft (Aishwarya, 2020). The technological evolution of submarine cables has been marked by significant advancements, such as the introduction of coherent transceiver technology and smart submarine line terminal equipment (SLTE), which have enhanced the capacity and reliability of these networks (Hadaway et al., 2016). These innovations have extended the economic life and competitiveness of submarine cables, allowing for larger capacities and reduced operational costs (Hadaway et al., 2016).

In addition to communication, submarine cables are also crucial for energy transmission, particularly in the context of offshore wind farms. The life cycle cost (LCC) model for high-voltage submarine cables highlights the importance of considering input costs, electricity loss, failure rates, and maintenance in the selection of optimal cable designs (Liu et al., 2015). The model suggests that the costs associated with electricity loss and failure are significant, comprising up to 30.8% and 62.0% of the LCC, respectively (Liu et al., 2015). This underscores the need for robust and efficient cable designs to ensure the economic viability of offshore energy projects.

Emerging technologies in submarine cable systems, such as Space Division Multiplexing (SDM) and Multi-Core Fiber (MCF), promise to further enhance the capacity and efficiency of these networks (Setianingrum et al., 2024; Takahashi et al., 2020). SDM, in particular, offers a practical solution for achieving high capacity and low cost-per-unit-capacity systems, with 32-fiber SDM systems identified as a near-future optimal design (Bolshtyansky et al., 2020). These advancements are crucial for meeting the growing demand for data transmission and ensuring the resilience of submarine cable networks against potential disruptions (Wang et al., 2022).

The strategic importance of submarine cables extends beyond their technical and economic aspects. They are considered a new economic trade route in the information age, acting as a commodity that underpins the digitization of activities and the ubiquity of cloud computing (Aishwarya, 2020). The business and environmental impacts of submarine cables are significant, influencing global market dynamics and necessitating careful consideration in their deployment and maintenance (Aishwarya, 2020). The development of comprehensive models for cable path planning and network design, which take into account factors such as cost, length, and resolution, is essential for optimizing the survivability and cost-effectiveness of submarine cable networks (Wang et al., 2022).

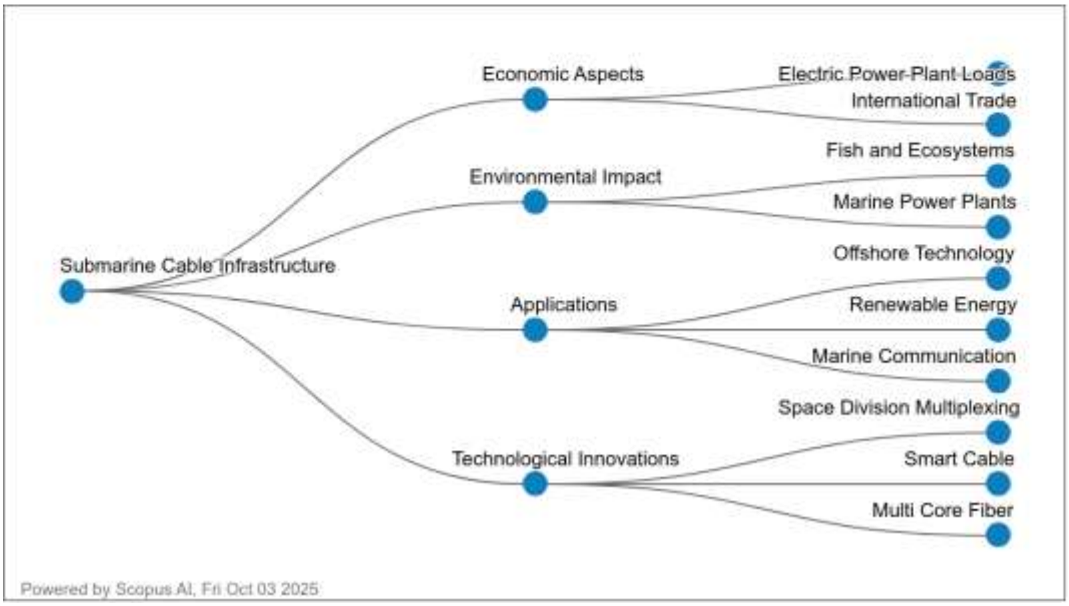

Figure 1: Concept Map Business Model For Submarine Cable Infrastructure

Figure 1 presents a conceptual framework for a potential business model for Submarine Cable Infrastructure: A Bibliometric Review, highlighting four main thematic areas: Economic Aspects, Environmental Impact, Applications, and Technological Innovations. Each of these areas' branches into more specific subtopics. Economic Aspects encompass Electric Power-Plant Loads and International Trade, emphasizing the infrastructure's role in energy distribution and global commerce. Environmental Impact includes Fish and Ecosystems, and Marine Power Plants, reflecting concerns about ecological balance and sustainable energy generation. The Applications domain covers Offshore Technology, Renewable Energy, Marine Communication, and Space Division Multiplexing, showing the infrastructure's diverse functional scope. Technological Innovations focus on advanced developments such as Smart Cables and Multi-Core Fiber, which are critical to improving capacity and performance. This conceptual map illustrates the multifaceted nature of submarine cable infrastructure, underscoring its strategic significance in global connectivity, economic development, environmental stewardship, and technological advancement. It serves as a comprehensive foundation for evaluating current and emerging business models in this sector.

In conclusion, the business models for submarine cable infrastructure are shaped by a complex interplay of technological advancements, economic considerations, and strategic imperatives. The continuous evolution of submarine cable technology, coupled with the growing demand for data and energy transmission, underscores the need for innovative and resilient cable designs. As the backbone of global communication and energy systems, submarine cables will continue to play a critical role in driving economic growth and facilitating the digital transformation of societies worldwide.

Research Question

1. What is the number of publications by year?
2. What are the top 10 most cited articles?
3. What are the top 10 countries based on the number of publications?
4. What are the popular keywords related to the study?
5. What is co-authorship by countries' collaboration?

Methodology

Bibliometrics is a methodological approach centered on the systematic collection, organization, and analysis of bibliographic data derived from scientific literature(Alves et al., 2021; Assyakur & Rosa, 2022; Verbeek et al., 2002). While it traditionally includes fundamental metrics such as identifying key journals, publication timelines, and influential authors (Wu & Wu, 2017), the field has evolved to incorporate advanced analytical tools like document co-citation analysis, which enables deeper insight into intellectual structures and thematic evolution within a research domain. A robust bibliometric review necessitates a meticulous, iterative process beginning with the strategic selection of keywords, followed by comprehensive literature searches and thorough data analysis. This rigorous approach facilitates the construction of a well-founded bibliography and enhances the reliability of the findings (Fahimnia et al., 2015). In this study, particular emphasis was placed on high-impact publications, as they offer critical perspectives and contribute significantly to the development of theoretical frameworks in the field. To ensure data integrity, Scopus recognized for its extensive and high-quality academic coverage was selected as the exclusive data source. (Al-Khoury et al., 2022; di Stefano et al., 2010; Khiste & Paithankar, 2017)Moreover, to uphold scholarly standards, only peer-reviewed journal articles were included in the analysis, with books and lecture notes intentionally excluded to maintain consistency and academic rigor (Gu et al., 2019). Data collection spanned publications from 2020 to December 2023, providing a contemporary and relevant foundation for analysis.

Data Search Strategy

A comprehensive and structured search strategy was employed to retrieve relevant academic literature concerning submarine or subsea fiber optic technologies using the SCOPUS database's advanced search function. The search string applied was: TITLE-ABS-KEY ((submarine OR subsea) AND (fiber OR fibre OR fiber)) AND PUBYEAR > 1960 AND PUBYEAR < 2026, which focused on publications containing these terms within their titles, abstracts, or keywords, and published between 1961 and 2025. To ensure the quality and relevance of the data, several filters were applied. The language was limited to English (LIMIT-TO (LANGUAGE , "English")), and only peer-reviewed journal articles and conference papers were included (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")), thereby excluding books, reviews, and other non-research content. Further refinement was applied by including only those publications that were in the final stage of publication (LIMIT-TO (PUBSTAGE , "final")), excluding in-press or incomplete works. Additionally, the subject areas were limited to Engineering, Computer Science, Business Management & Accounting, and Energy (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "COMP") OR LIMIT-TO (SUBJAREA , "BUSI") OR LIMIT-TO (SUBJAREA , "ENER")) to maintain disciplinary relevance and ensure the inclusion of technically focused research. No specific timeline filter was applied beyond the year range, which allowed for a broader historical context. The screening criteria mirrored the search filters, with inclusion based on English-language publications in the selected subject areas, limited to journal articles and conference proceedings in the final publication stage. Exclusion criteria included non-English works, publications from unrelated subject areas, literature types such as books and reviews, and documents still in press. The search was conducted in October 2025, resulting in a final dataset of 1,989 relevant documents. This rigorous search and screening strategy ensured a focused and high-quality collection of literature, providing a robust foundation for analyzing developments in submarine and subsea fiber optic systems from both technological and industry perspectives.

Table 1: The Search String

Scopus	**TITLE-ABS-KEY ((submarine OR subsea) AND (fiber OR fibre OR fiber)) AND PUBYEAR > 1960 AND PUBYEAR < 2026 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "COMP") OR LIMIT-TO (SUBJAREA , "BUSI") OR LIMIT-TO (SUBJAREA , "ENER"))** Access date: October 2025

Table 2: The Selection Criterion in Searching

Criterion	**Inclusion**	**Exclusion**
Language	English	Non-English
Subject Area	Engineering, Computer Science, Energy, Business Management & Accounting	Other subject area
Timeline	N/A	< 2026
Literature type	Journal (Article), Conference	Book, Review, Conference Review
Publication Stage	Final	In Press

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Data Analysis

VOSviewer is a robust and accessible bibliometric analysis software developed by Nees Jan van Eck and Ludo Waltman at Leiden University in the Netherlands (van Eck & Waltman, 2010, 2017). It has gained widespread recognition for its advanced capabilities in visualizing scientific knowledge structures, offering intuitive network visualizations, item clustering, and density mapping. Designed for versatility, VOSviewer enables the detailed exploration of co-authorship, co-citation, and keyword co-occurrence networks, making it an indispensable tool for researchers aiming to uncover intellectual patterns and thematic connections within vast bodies of literature. Its continuously updated, interactive interface supports the dynamic analysis of large-scale bibliometric datasets, accommodating both novice and expert users with ease (van Eck & Waltman, 2010, 2017)

A defining strength of VOSviewer lies in its ability to translate complex bibliometric data into clear, visually interpretable maps and charts. Its network visualization features allow for in-depth analysis of keyword relationships, citation structures, and author collaborations, facilitating a holistic view of the research landscape. With built-in support for metric computation and high adaptability to diverse bibliometric sources, the software empowers scholars to generate meaningful, data-driven insights across multiple disciplines. For this study, bibliometric data, including publication years, article titles, author names, journals, citations, and keywords, were retrieved in PlainText format from the Scopus database, covering the period from 1961 to October 2025. These datasets were analyzed using VOSviewer version 1.6.20, employing its clustering and mapping techniques to uncover relational structures.

Unlike traditional Multidimensional Scaling (MDS), which relies on similarity indices such as cosine or Jaccard coefficients, VOSviewer situates items in a low-dimensional space using a more refined normalization technique—association strength (ASij)—to more accurately represent inter-item relatedness (Appio et al., 2014; van Eck & Waltman, 2010; Van Eck & Waltman, 2007). While sharing conceptual similarities with MDS in terms of spatial representation (Appio et al., 2014), VOSviewer surpasses it in bibliometric applications by focusing on co-occurrence frequency normalization, enhancing the reliability and interpretability of generated visualizations (Van Eck & Waltman, 2007). This methodological sophistication underscores VOSviewer's continued relevance as a leading tool in contemporary bibliometric research.

Result and Discussion

This section presents the key findings derived from the bibliometric analysis of 1989 peer-reviewed journal articles on submarine cables published between 1961 and 2025. The results are organized to highlight the productivity of subject areas, the most influential articles and authors, country-level contributions, emerging thematic keywords, and international research collaborations. Using tools like Scopus Analyzer and VOSviewer, the analysis offers valuable insights into the intellectual structure, research trends, and global engagement surrounding the intersection of submarine cables and cable technology.

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Number Of Publications By Year

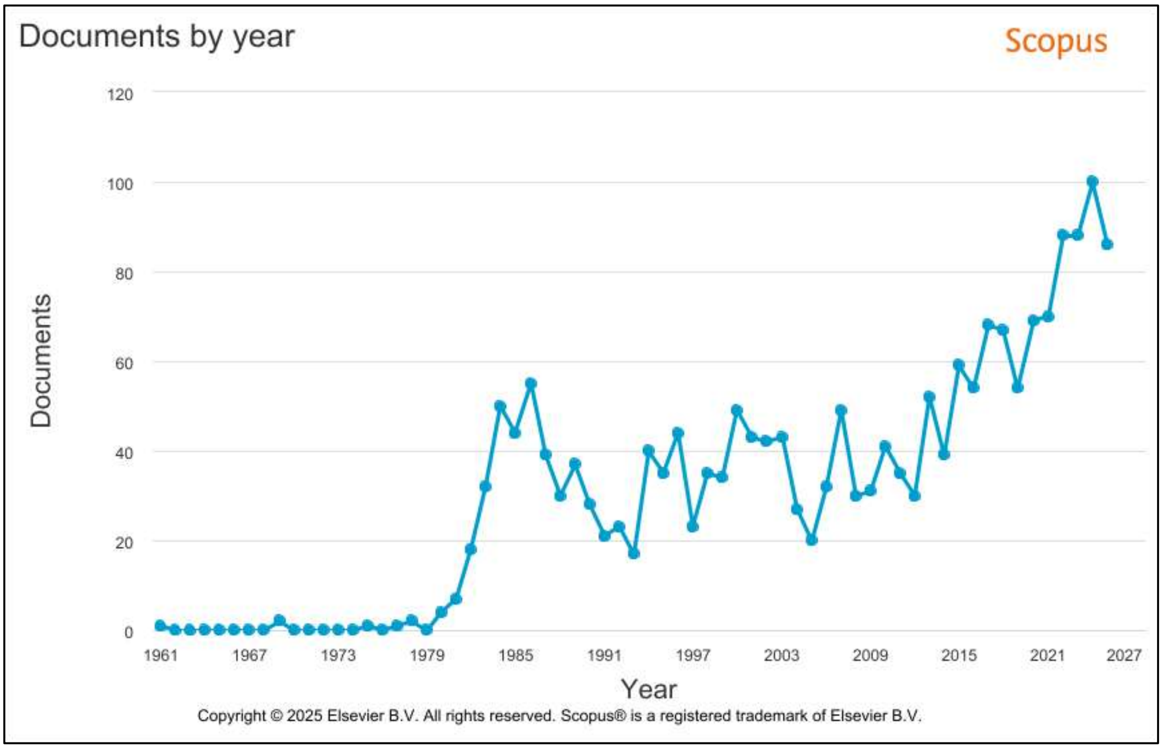

Figure 2: Trend Of Publication By Years

The data in Figure 2 shows a clear upward trend in the number of publications over time, particularly accelerating from the early 2000s onward. In the earlier decades from 1961 through the 1990s publication numbers were relatively low, often in the single or low double digits. This limited output reflects the nascent stage of subsea fiber optic technology and related research fields during those years. Technological limitations, lower global demand for high-speed communication, and fewer research institutions focusing on this area contributed to this slow growth. A notable increase begins in the early 2000s, likely driven by the global expansion of the internet, the rise of international data traffic, and growing interest in submarine communication systems to support global connectivity. By the mid-2010s, consistent annual publication numbers above 50 reflect a maturation of the field and growing academic and industrial interest.

From 2020 onward, publication activity increases even more sharply, peaking in 2024 with 100 publications. This recent surge is likely due to several converging factors: increasing global reliance on digital infrastructure, expansion of cloud services and data centers, and heightened interest in resilient subsea communication systems due to geopolitical tensions and climate-related risks. The COVID-19 pandemic may have also contributed to the acceleration of research in digital connectivity and remote sensing technologies. The high number of publications in 2023–2025 reflects both growing investment in advanced subsea technologies (such as smart cables, 3D printing in marine construction, and fiber sensing) and improvements in academic collaboration and publication platforms. This sustained growth indicates that the field is not only technologically important but also increasingly recognized as strategically vital to global infrastructure and information security.

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Analysis of Most Cited Articles

Table 3: Most Cited Author

Authors	Year	Source title	Cited by
(Huang et al., 2021)	2021	Nature Electronics	219
(Shahinpoor, 1992)	1992	Smart Materials and Structures	200
(Zhang et al., 2015)	2015	IEEE Transactions on Industry Applications	184
(Messager et al., 2002)	2002	Composite Structures	139
(Hasvold et al., 1997)	1997	Journal of Power Sources	116
(Li et al., 2021)	2021	Additive Manufacturing	101
(Tornatore et al., 2005)	2005	IEEE Journal on Selected Areas in Communications	98
(Lv & Li, 2018)	2018	Sensors and Actuators A: Physical	94
(Frangopol & Recek, 2003)	2003	Probabilistic Engineering Mechanics	93
(Omer et al., 2009)	2009	IEEE Systems Journal	92

The citation data reveal that the most highly cited work among the listed authors is by Huang et al. (2021), with 219 citations for a paper on a silicon photonic–electronic neural network for fiber nonlinearity compensation, published in *Nature Electronics*. This high citation count is likely due to the paper's intersection of cutting-edge fields such as silicon photonics, neural networks, and optical communications, all of which are highly active and rapidly evolving research areas. Being published in a high-impact journal like *Nature Electronics* also significantly boosts visibility and citation potential. Similarly, Shahinpoor's 1992 work on biomimetic swimming robots has received 200 citations, indicating the enduring relevance of foundational research in smart materials and robotics. Although older, this work likely continues to be cited due to its conceptual nature and broad applicability in underwater robotics and soft actuator design.

In the mid-range of citations, papers like Zhang et al. (2015) and Messager et al. (2002) demonstrate the impact of practical engineering problems, such as rotor sleeve design and underwater composite vessel optimization, which are of sustained interest in electrical and marine engineering communities. Li et al. (2021) and Tornatore et al. (2005) show how newer research on innovative materials and optical network design is gaining traction, albeit with lower citation counts that may increase over time. Lower-cited but still significant works like those by Lv & Li (2018), Frangopol & Recek (2003), and Omer et al. (2009) focus on niche or specialized topics such as online cable monitoring, probabilistic analysis, and telecommunication system resilience. These are valuable within their domains but may have limited crossover appeal. Overall, citation trends in this dataset are shaped by factors including

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publication year, journal impact, topic novelty, and cross-disciplinary relevance, with newer papers in emerging fields or older foundational works tending to attract the highest attention.

Top 10 Countries Based on Number of Publications

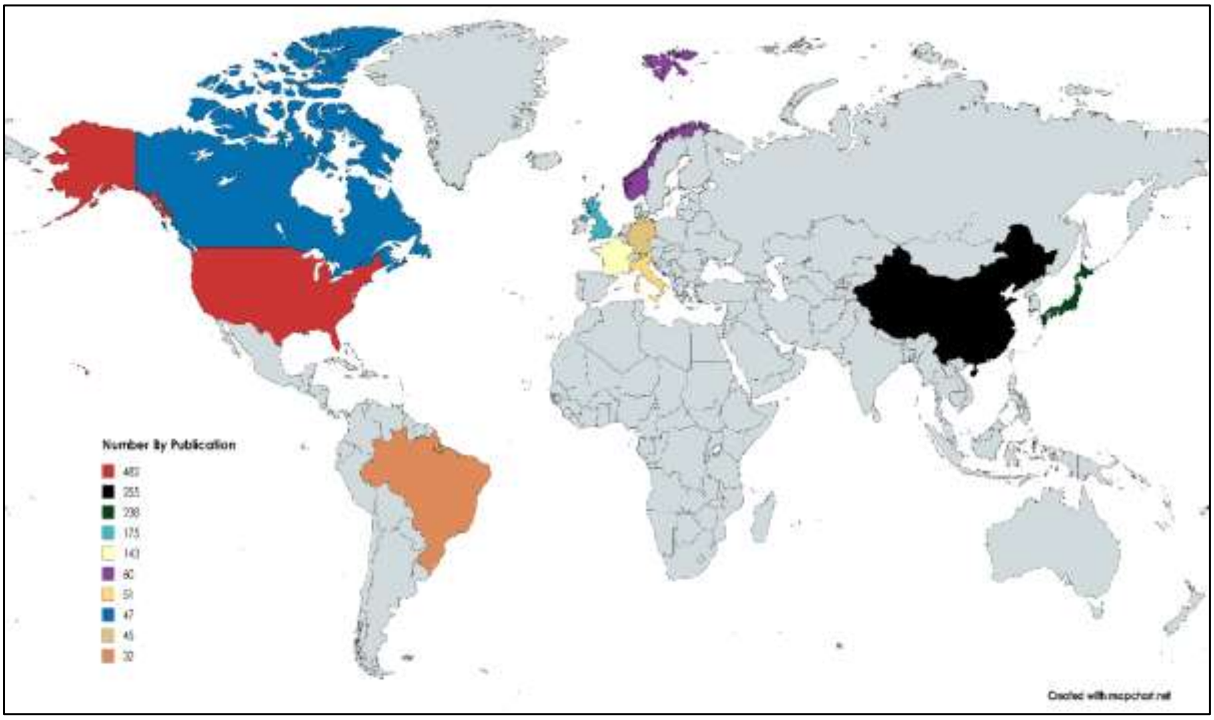

Figure 3: Country Mapping Based On The Number Of Publications

The publication data reveals that the United States leads significantly with 482 publications, nearly double that of the second-highest contributor, China (255), followed closely by Japan (238). This dominant position of the U.S. can be attributed to its longstanding investment in advanced communication infrastructure, robust research funding, and a well-established network of academic and industry collaborations in telecommunications and subsea technologies. Additionally, the presence of major tech and defense corporations, such as Google, SubCom, and AT&T, which are directly involved in subsea cable development, further fuels research output. China's strong presence reflects its rapid technological advancements and strategic investments in global digital infrastructure, including the Belt and Road Initiative, which incorporates digital components like undersea fiber networks. Japan's high output is supported by its early adoption of submarine cable systems and its status as a technological hub in Asia, with companies like NEC and NTT contributing heavily to the field.

In contrast, European countries like the United Kingdom (175), France (143), Norway (60), Italy (51), and Germany (45) demonstrate moderate levels of publication, which are consistent with their participation in international subsea communication projects and their academic capacities. The UK and France have historical ties to transatlantic cable development and maintain active research roles. Norway, despite its smaller size, appears prominently due to its geographic positioning along key subsea routes and its investments in offshore and marine technologies. Canada and Brazil, while having smaller outputs (47 and 32, respectively), are still active contributors, likely due to their coastal geographies and involvement in regional subsea cable projects. Overall, the distribution of publications reflects both technological

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capabilities and geopolitical interests in global data infrastructure, with higher outputs generally aligning with economic strength, technological maturity, and strategic participation in global telecommunications networks.

Popular Keywords Related to Submarine Cables Study

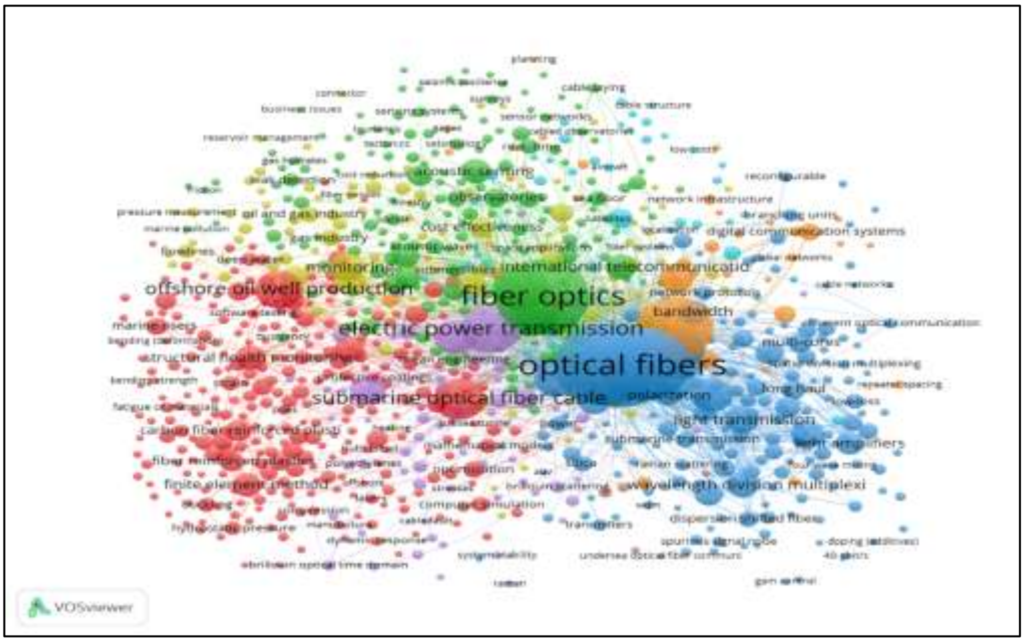

Figure 4: Network Visualization Map Of Keywords' Co-Occurrence

Co-occurrence analysis of author keywords in VOSviewer is a bibliometric method used to explore the relationships and thematic structures within a body of scientific literature by identifying how often keywords appear together in the same documents. In this context, it helps researchers visualize the intellectual landscape of a research domain. VOSviewer creates a network map where each node represents a keyword, and the links between them indicate co-occurrence frequency essentially mapping how topics are interconnected. Larger nodes or stronger link strengths signal keywords that are more central or widely discussed across the literature. By applying clustering algorithms, related keywords are grouped together into thematic clusters, providing insights into subfields and research directions within the domain.

In this analysis, a full counting method was employed, meaning each occurrence of a keyword co-occurrence was fully counted rather than fractionally weighted. A minimum occurrence threshold of five was set, out of 5,840 total keywords, resulting in 898 keywords included in the network. Additionally, the minimum cluster size was set to eight, which led to the formation of eight distinct clusters. The analysis highlights prominent keywords such as "optical fibers," "submarine cables," and "fiber optics," which had high occurrence and total link strength values, signifying central roles in the field. These findings contribute to the body of knowledge by identifying major research themes (e.g., telecommunication infrastructure, sensing technologies, offshore systems), revealing interdisciplinary connections (such as between optical communication and underwater acoustics), and helping guide future research focus by exposing emerging or underexplored areas within this domain.

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Co-authorship based on Countries Collaboration

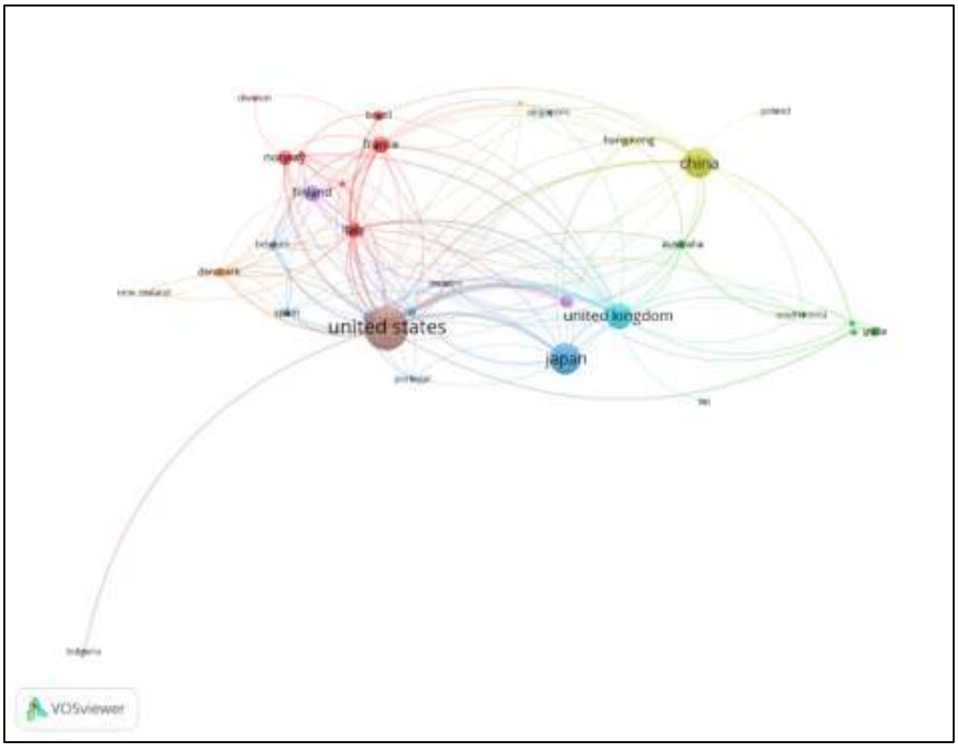

Figure 5: Co-Authorship Collaborations For Countries Involved In Research

The concept of co-occurrence co-authorship by countries, as visualized using VOSviewer, refers to mapping and analyzing collaborative relationships between nations based on shared authorship of academic publications. Each node in the network represents a country, and connections (or links) between nodes indicate instances where researchers from those countries have co-authored publications. The strength of these connections, known as Total Link Strength (TLS), reflects the frequency and intensity of these collaborations. This approach helps to identify global research partnerships, central players in international scientific collaboration, and the structure of knowledge exchange across borders.

To generate this specific network visualization, VOSviewer was configured with the full counting method, meaning each co-authored paper counts fully for all countries involved. A minimum threshold of five publications per country was set, out of which 34 countries met the inclusion criteria from a total of 123. Additionally, a minimum cluster size of five was applied, resulting in eight distinct clusters. These clusters reveal collaboration groupings, often based on geographical proximity or shared research interests. The results show that countries like the United States, the United Kingdom, and China are central to global research collaboration, indicated by their high number of documents, citations, and strong link strengths. This mapping contributes to the body of knowledge by highlighting the pivotal roles certain countries play in driving and connecting global research networks, informing policymakers and institutions on how to strengthen international academic partnerships.

Conclusion

This study set out to provide a comprehensive bibliometric assessment of submarine cable infrastructure research, addressing questions related to publication dynamics, influential works, national contributions, keyword trends, and collaborative networks. The analysis of nearly two thousand publications demonstrates that the field has expanded rapidly over the last two decades, with a particularly sharp rise in output after 2020, reflecting the intensifying global reliance on resilient digital and energy infrastructures. Highly cited works reveal the dual influence of pioneering engineering studies and more recent advances at the intersection of photonics, smart materials, and network design. At the geographical level, the United States, China, and Japan dominate the landscape, while European and coastal economies contribute through regional expertise and strategic participation. Keyword clustering and co-authorship mapping further underscore the growing complexity of this research domain, where themes of optical communication, sensing technologies, and offshore systems converge.

The contribution of this study lies in its systematic mapping of the intellectual and collaborative structure of submarine cable research. By visualizing knowledge clusters and highlighting emerging thematic directions, the findings not only consolidate existing scholarship but also provide a foundation for guiding future inquiry. The results hold relevance for both academia and industry, offering evidence-based insights for investment decisions, policy formulation, and the development of sustainable and resilient subsea systems.

While this study delivers a broad overview of the field, certain limitations should be acknowledged. The exclusive reliance on a single database and the exclusion of non-English publications may restrict coverage. Future research would benefit from triangulating across multiple data sources, incorporating longitudinal approaches, and examining intersections with pressing issues such as environmental sustainability, energy transition, and geopolitical risk.
In sum, this bibliometric review demonstrates that submarine cable infrastructure has evolved into a strategically vital field that underpins the global digital economy and energy transition. Bibliometric approaches serve as a powerful lens for understanding its intellectual trajectory, identifying opportunities for innovation, and strengthening international collaboration. As submarine cables continue to expand in scale and strategic importance, rigorous scholarly attention will remain essential to shaping the future of this critical infrastructure.

Acknowledgements:	The authors express sincere gratitude to the Universiti Teknologi Malaysia and colleagues who provided valuable insights and encouragement throughout this study. The appreciation is also extended to the administrative and technical teams involved in data management and analysis. The completion of this work reflects a shared commitment to academic inquiry and the betterment of research in the submarine cable field.
Funding Statement:	No Funding
Conflict of Interest Statement:	The authors declare that there is no conflict of interest regarding the publication of this paper. All authors have contributed to this work and approved the final version of the manuscript for submission to the International Journal of Innovation and Industrial Revolution (IJIREV).

Ethics Statement:	This study was conducted in accordance with ethical research standards. All procedures involving human participants were reviewed and approved by the Universiti Teknologi Malaysia Research Ethics Committee (UTM REC). Informed consent was obtained from all participants prior to data collection. Participation was voluntary, and respondents were assured of confidentiality and anonymity. The data collected were used solely for academic purposes.
Author Contribution Statement:	All authors contributed significantly to the development of this manuscript. Mohamad Hidayat Ghazali was responsible for the conceptualization, methodology, and overall supervision of the study. Hazilah Mad Kaidi handled data collection, analysis, and interpretation of results. Shamsul Sarip contributed to the literature review, drafting, and critical revision of the manuscript. All authors read and approved the final version of the manuscript prior to submission.

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