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Navigating Marine Propulsion: Trends, Challenges, and Emerging Technologies

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Abstract

This study presents a comprehensive bibliometric analysis of marine propulsion research to investigate its historical development, current landscape, and future directions. Through the analysis of scientific literature retrieved from the Scopus database, the study employs Biblioshiny and VOSviewer software for data visualization and trend exploration. The analysis uncovers key research trajectories, dominant thematic areas, influential keywords, and leading contributing countries. The results reveal a growing global focus on sustainable and energy-efficient propulsion technologies, with particular attention to electric and hybrid systems. However, the adoption of clean propulsion alternatives remains constrained by technological limitations and economic feasibility, indicating that electric propulsion is still in a relatively nascent stage within the maritime sector. As the maritime industry advances toward decarbonization, this study highlights the untapped potential of alternative propulsion systems, including the relatively underexplored domain of pneumatic propulsion.

Keywords: *Pneumatic propulsion, compressed air energy storage, Maritime, Bibliometric analysis, Sustainable transportation.*

1. Introduction

Maritime transportation plays a vital role in global trade and economic development, serving as the backbone of international commerce. Maritime transport facilitates the movement of approximately 80% of international goods by volume [1]. It plays a central role in connecting economies, enabling the exchange of raw materials, energy resources, manufactured products, and food supplies across continents. One of the key advantages of maritime transport is its cost-efficiency, especially for bulk cargo and long-distance shipments. Ships can carry massive quantities of goods in a single voyage, reducing per-unit transportation costs and lowering environmental impact compared to other modes of transport [2]. Additionally, maritime transport is generally more fuel-efficient and offers greater cargo capacity, making it ideal for global logistics. The extensive network of ports and shipping routes also enhances global accessibility and supply chain resilience, underlining the strategic importance of maritime transport in today's interconnected world. Maritime transport, due to its ability to carry large volumes of cargo in a single voyage, generally results in a lower environmental impact per unit of goods transported. Although it contributes to CO₂ emissions, these emissions are significantly lower when compared to road or air transport on a per-ton-kilometer basis, making maritime transport a relatively more environmentally friendly option [3]. The lower carbon footprint is indicative of reduced fuel consumption, which further enhances its sustainability credentials [4]. However, despite these advantages, maritime transport also presents several drawbacks. Environmental concerns persist, particularly regarding air quality in coastal and port areas, where emissions from ships contribute to localized pollution [5]. Additionally, maritime transport is considerably slower than other modes, such

as air transport, with shipping routes often taking several days or even weeks to complete, whereas air freight can accomplish the same in less than a day. Furthermore, maritime operations are highly dependent on weather conditions; adverse events such as storms, hurricanes, or rough seas can lead to significant delays or even accidents [6]. Safety remains another critical issue, as maritime transport is susceptible to operational risks including collisions, grounding, and human error. While modern navigation and safety technologies have improved overall reliability, the inherent risks of maritime operations remain a concern [7].

The history of marine propulsion has evolved significantly over the centuries, reflecting advances in engineering and the changing demands of global navigation. Early ships relied solely on human power, using paddles or oars, before wind power became dominant with the widespread use of sails in ancient civilizations. The Age of Sail marked a period of significant exploration and trade expansion. The Industrial Revolution introduced steam propulsion, revolutionizing maritime transport by allowing ships to travel independently of wind conditions. Steam engines, initially powered by coal and later by oil, led to the development of more reliable and faster vessels. In the 20th century, diesel engines became the primary mode of propulsion due to their greater efficiency and power. More recently, the maritime industry has begun exploring alternative propulsion technologies, including liquefied natural gas (LNG), electric and hybrid systems, and even wind-assisted propulsion, as part of efforts to reduce environmental impact and enhance energy efficiency [8].

Diesel engines have become the dominant mode of propulsion in modern maritime transport due to their high efficiency, durability, and reliability over long distances.

The main characteristic of diesel engines is their fuel efficiency, which allows ships to travel vast distances with relatively low fuel consumption compared to steam or gasoline engines [9].

Additionally, diesel engines offer high torque at low speeds, making them well-suited for the heavy-duty demands of marine vessels. However, diesel engines also present several disadvantages, as they are significant contributors to air pollution, emitting nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter, which affect both human health and the environment [10]. Furthermore, the reliance on fossil fuels raises concerns about greenhouse gas emissions and long-term sustainability. In response, the maritime industry is increasingly exploring cleaner alternatives and emission control technologies to mitigate the environmental impact of diesel propulsion systems.

One of these responses is the utilization of electrical propulsion systems, which are increasingly being adopted in the maritime industry as a cleaner and more sustainable alternative to conventional diesel engines [11]. One of the primary advantages of electric propulsion is its significant reduction in greenhouse gas emissions and air pollutants, making it an environmentally friendly option, especially in emission-controlled areas and coastal zones. Electric systems also operate more quietly and with less vibration, enhancing onboard comfort and reducing noise pollution in marine ecosystems. Furthermore, electric propulsion allows for greater flexibility in ship design and improved energy efficiency, particularly when integrated with renewable energy sources or hybrid configurations. However, the widespread adoption of electric propulsion faces several challenges. The current limitations in battery energy density and storage capacity restrict its use to short-distance or smaller vessels, such as ferries and tugboats. Additionally, the high initial investment cost and the need for supporting infrastructure, such as charging stations and grid upgrades at ports, remain significant barriers.

Pneumatic propulsion in maritime applications has recently evolved as a niche system for propulsion of maritime vessels. Pneumatic propulsion involves the use of compressed air to generate thrust, typically through the expansion of high-pressure air in a turbine or piston system. These systems can offer high responsiveness and precise control, which is particularly useful in vessels with predetermined routes and schedules [12]. Pneumatic propulsion can reduce reliance on fossil fuels when integrated with renewable energy sources to compress air, contributing to lower emissions. It also eliminates risks associated with fuel combustion, such as fires or spills, enhancing operational safety. In the context of maritime transportation, bibliometric analysis is especially valuable for several reasons. First, it enables the monitoring of developments in areas such as ship propulsion technologies, environmental regulations, port management, and logistics. It also highlights emerging topics like green shipping, digitalization, or autonomous vessels, guiding research priorities and funding decisions. Additionally, bibliometric tools can identify influential authors, institutions, and journals, fostering collaboration and knowledge sharing across disciplines. Numerous studies have been conducted on mari-

time transport, focusing on maritime tourism research [13] and maritime transport resilience [14]. Some also carried out bibliometric studies on alternative marine fuel [15], maritime inspection [16], and green shipping [17].

This paper examines the evolution of marine propulsion research using a comprehensive bibliometric framework grounded in science mapping and innovation transition theory. Through the systematic analysis of scholarly literature, the study identifies dominant research trajectories, thematic clusters, and keywords' evolution that have shaped marine propulsion development across different periods. The analysis is further used to interpret how technological priorities have shifted in response to environmental regulation, energy efficiency requirements, and sustainability imperatives. Accordingly, the paper critically evaluates the extent to which current propulsion pathways, particularly electric and hybrid systems, address the limitations of conventional diesel technologies. The study also explores under-investigated propulsion concepts, such as pneumatic propulsion, as part of an emerging sustainability-oriented transition in marine transport.

2. Methodology

For the bibliometric analysis, Scopus database is used to extract the data, which is imported into Biblioshiny and VOSviewer for visualization. Scopus is selected as the primary database because it is a widely recognized and comprehensive source of peer-reviewed literature, covering journals, conference proceedings, and books, while offering advanced analytical tools that enable systematic monitoring and evaluation of global research output across disciplines, thereby reducing the risk of overlooking relevant international studies. In addition, no exclusions are applied with respect to document types or subject area filters, ensuring an inclusive and unbiased retrieval of the relevant literature. The following search query is considered to include all publications related to marine propulsion:

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((TITLE-ABS-KEY(Propulsion) AND TITLE-ABS-KEY(Ship* OR Boat* OR Maritime OR Marine* OR Ferry OR Ferries)) AND (LIMIT-TO ( LANGUAGE, "English" ) ) )
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Scopus is also used directly to analyze and visualize three key aspects: related subject areas, annual scientific production, and number of publications per country. Biblioshiny is responsible for presenting an overview of the bibliometric analysis and analyzing the most occurring keywords in this field. Keyword analysis undergoes data cleaning to remove highly occurring, obvious words that may hinder the visualization of crucial areas. Additionally, the keywords are further analyzed through VOSviewer, which in turn creates thematic clusters that help identify the key areas in marine propulsion and the most related keywords.

3. Results and Discussion

3.1 Overview

According to the search query presented in the previous section, 689 documents related to marine propulsion were

published during the period of 1925-2025, as shown in Fig. 1. In the current bibliometric analysis, the timespan was kept as the default to include all research publications in this field and observe the variation in scientific production over time. The average annual growth rate is relatively low, accounting for 1.62%. The total number of authors who contributed to marine propulsion is 917, where 108 of them are authors of single-authored documents. However, the single-authored documents accounted for 412, representing around 60% of the total number of publications. Additionally, international co-authorships are considered low, with a percentage of 8.8%. This shows that this field of study is highly affected by various factors, particularly the location and transportation sector in the investigated region/country. Consequently, this highlights that many of these studies are related to case studies focused on particular regions rather than general research.

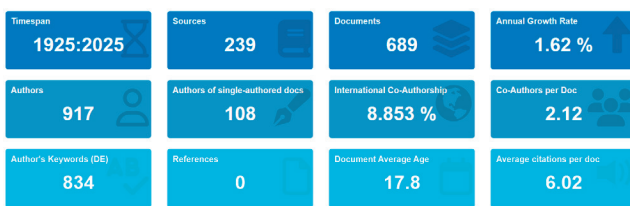


Fig. 1. Main information

The analysis of subject areas in marine propulsion research reveals a strong dominance of the Engineering field, which accounts for 91.4% of the total documents. This overwhelming focus indicates that most studies in this domain are technical in nature, emphasizing design, development, and optimization of propulsion systems. Energy is the second most represented area, comprising 16%, reflecting the growing interest in fuel efficiency, alternative fuels, and sustainable energy solutions within maritime transportation. Environmental Science (8.9%) and Social Sciences (8%) follow, highlighting increasing attention toward environmental impacts and societal dimensions of marine propulsion. Other contributing disciplines include Mathematics (4.9%), Earth and Planetary Sciences (4.8%), and Computer Science (4.4%), suggesting interdisciplinary involvement in modelling, simulations, and digital innovations. The presence of other areas (7.8%) further underscores the breadth of research, though the core remains firmly rooted in engineering and energy-related studies. Fig. 2 shows the number of publications related to each subject area in marine propulsion publications.

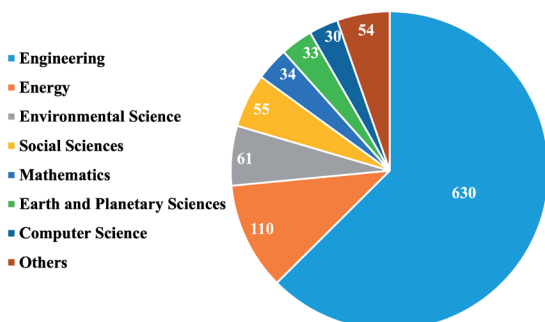


Fig. 2. Related subject areas

3.2 Research trends

The publication trend in marine propulsion research shows a slow start, with only a single document published as early as 1925. Following this, the research activity remained minimal until the mid-1980s, with no more than a few publications per year (as seen in Fig. 3). Starting from 1974, when another document appeared, the number of publications began to gradually increase. The field saw modest growth during the 1980s and early 1990s, with notable increases in 1994 (11 documents) and 1995 (30 documents), marking the beginning of more sustained academic interest. From the mid-1990s onward, the number of publications rose more consistently, peaking intermittently in certain years such as 1997 (33 documents) and 2005 (32 documents). The period between 2000 and 2010 saw steady outputs, fluctuating between 15 and 27 publications annually. A slight dip occurred between 2008 and 2014, but interest picked up again post-2015. The most significant growth occurred in the last few years, with notable peaks in 2021 (37 documents) and 2023 (34 documents), indicating a renewed and intensified focus on marine propulsion, likely driven by emerging technologies and global sustainability goals. Overall, the data reflect a long-term upward trend, particularly accelerating over the past three decades.

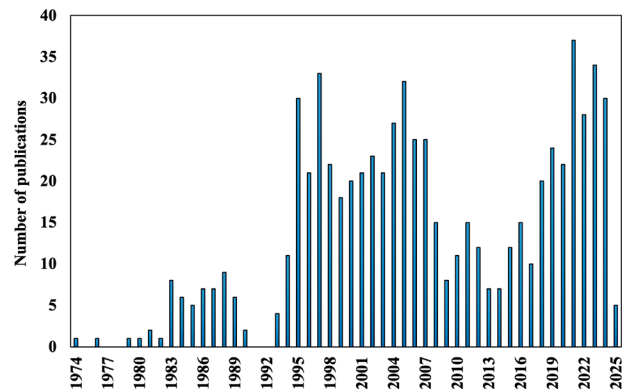


Fig. 3. Annual scientific production

3.3 Keywords analysis

Figs. 4a and 4b present word clouds illustrating the most frequently occurring keywords in marine propulsion literature, based on Indexed Keywords (Keywords Plus) and Authors' Keywords, respectively. These visualizations help identify the central themes and evolving areas of interest in the field. For better clarity and visual balance, certain highly common or overly generic terms were excluded: "ship propulsion" was removed from the indexed keywords, while "vessel," "catamaran," "ferry," and "passenger ship" were excluded from the authors' keywords. This exclusion was applied solely at the visualization stage and was guided by the need to prevent dominant terms from overshadowing more specific and informative keywords. As these generic terms broadly describe the domain rather than distinct research directions, their inclusion would reduce the interpretability of the word clouds and potentially mask emerging or special-

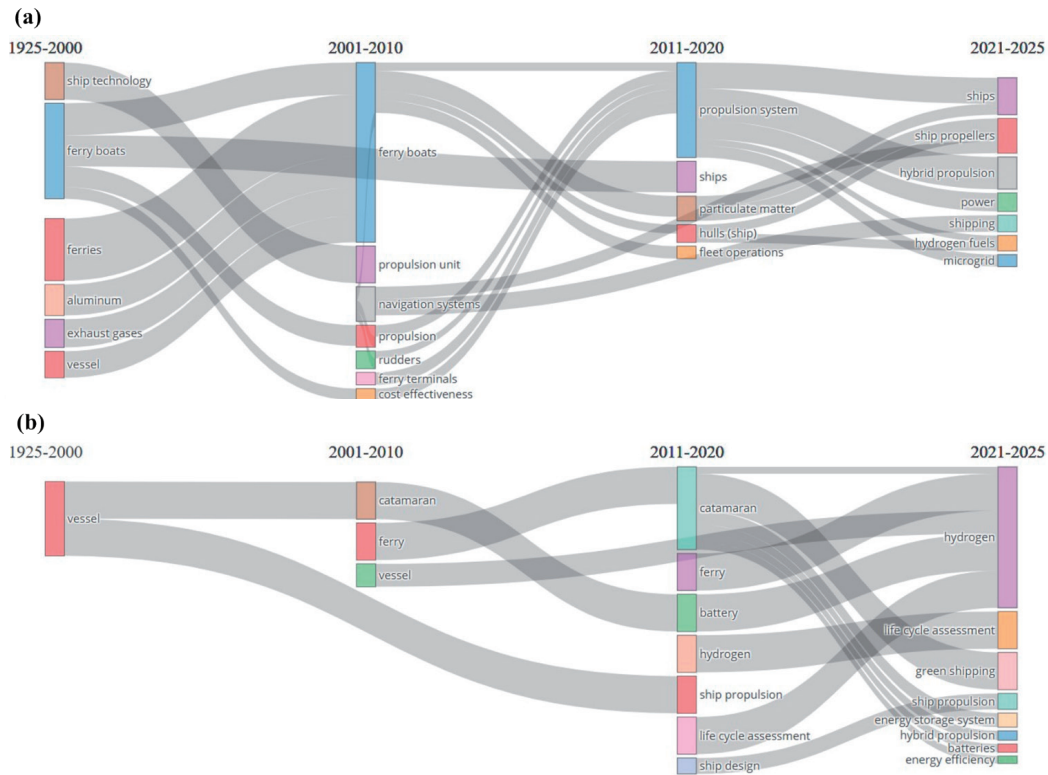


Fig. 7. Thematic evolution within the marine propulsion research field: (a) keywords plus and (b) authors' keywords

3.4 Countries contribution

Fig. 8 presents the top ten contributing countries in marine propulsion research, based on the number of publications. Italy leads the list with a notable margin, contributing 65 publications, which reflects its strong maritime industry and research focus on propulsion technologies. The United States follows with 39 publications, indicating active involvement, likely driven by both academic and naval interests. The United Kingdom and Norway contribute 25 and 24 publications respectively, aligning with their long-standing maritime heritage and investment in marine innovation. Notably, most contributions come from Europe, as 8 out of the top 10 countries, namely Italy, United Kingdom, Norway, Germany, Finland, Poland, Denmark, and the Netherlands, highlighting the continent's dominant role in advancing research and development in marine propulsion.

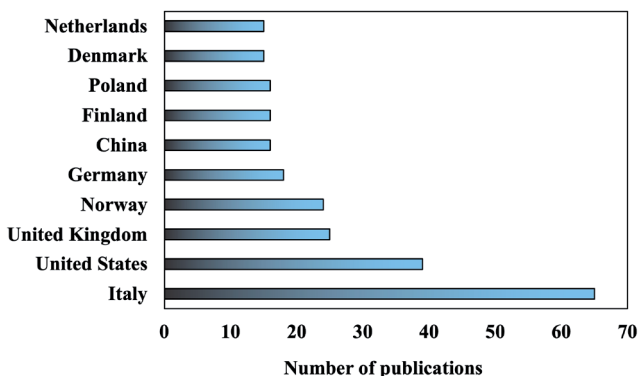


Fig. 8. Countries' contribution to the scientific production

4. Sustainable Transition in Marine Propulsion

4.1 Current limitations and challenges

One of the significant gaps in both academic research and practical applications within maritime transportation lies in the continued reliance on diesel-based propulsion systems. Despite their widespread use, these systems are known to contribute heavily to environmental pollution, emitting greenhouse gases and other harmful pollutants. Based on the conducted bibliometric analysis, it is evident that researchers and stakeholders are increasingly turning their attention toward environmentally benign alternatives that align with global sustainability goals. Among these, electric propulsion has emerged as a prominent area of interest, offering the potential for cleaner operation and reduced emissions. However, despite this growing attention, electric propulsion technology in the maritime sector still lacks strong and conclusive evidence to prove its feasibility as a full replacement for traditional diesel engines. Multiple economic and technological challenges have hindered their widespread adoption, including high initial investment costs, limitations in battery energy density, and the need for specialized infrastructure. Given these challenges, it is essential to explore other innovative and sustainable propulsion options, such as pneumatic propulsion, which utilizes compressed air to generate thrust.

4.2 Pneumatic propulsion

Compressed air energy storage (CAES) plays an important role in pneumatic propulsion by enabling energy to be

stored in the form of pressurized air and later converting it directly into mechanical motion. In such systems, electrical or mechanical energy is first used to compress air into tanks, effectively storing energy without the chemical degradation associated with batteries. This direct conversion from stored pressure to motion allows pneumatic propulsion systems to be mechanically simple, responsive, and capable of high-power output over short durations [18].

The utilization of CAES in pneumatic propulsion is particularly attractive in applications where cleanliness, safety, and rapid energy discharge are priorities. Compressed air is non-flammable and produces no exhaust emissions at the point of use, thus pneumatic propulsion is well-suited for maritime applications.

In [19], the performance of pneumatic propulsion was evaluated alongside electric propulsion systems powered by electrochemical batteries. A life cycle analysis was also conducted to assess the environmental benefits, particularly regarding carbon dioxide emissions. The results revealed that pneumatic propulsion not only matched, but in some aspects, outperformed electric systems, providing approximately 6% more thrust and achieving an annual carbon footprint reduction of 307 kg CO₂. These findings highlight the practical advantages of pneumatic systems, especially for applications like ferryboats, where routes are consistent in both distance and direction, making them well-suited for the operational characteristics of compressed air propulsion.

Another recent study proposed a pneumatic propulsion system as a sustainable alternative to replace a diesel-powered ferry operating in Finland [12]. The research examined all essential components of the system, including air motors, compressors, storage tanks, heat exchangers, and auxiliary energy sources like battery banks and electric chargers. The proposed setup, designed to match the ferry's daily energy requirement of 3.58 GJ, featured eight 60 kW air motors and a 50 m³ compressed air tank at 150 bar, recharged using a 132 kW compressor within 6.2 hours. Compared to the diesel system, which consumes over 55,000 liters of fuel annually, the pneumatic configuration demonstrated substantial environmental and economic advantages, including projected savings of approximately \$73,000 and 120 tons of CO₂ emissions per year, with an estimated payback period of 8.1 years.

5. Conclusion

In conclusion, the bibliometric analysis highlights a clear shift in marine propulsion research toward more sustainable and environmentally friendly solutions. The increased occurrence of keywords such as “electric propulsion,” “energy efficiency,” “fuel cells,” and “hydrogen” reflects a growing academic and industrial interest in cleaner technologies. However, despite the gradual appearance of electric propulsion systems, the analysis suggests that the maritime sector still lacks a comprehensive and unified strategy for transitioning to fully sustainable propulsion methods. Electric propulsion, although promising, remains relatively immature within the industry and is

likely to face a range of challenges, particularly related to technological readiness, high implementation costs, limited infrastructure, and concerns about long-term reliability. These obstacles indicate the need for further development and support before such systems can be widely adopted. Given these limitations, it is essential to explore alternative propulsion technologies that offer environmental benefits while potentially overcoming the barriers associated with electric systems. One such emerging solution is pneumatic propulsion, which relies on compressed air to generate thrust. Although still in its early stages and not yet extensively tested in real-world maritime applications, pneumatic propulsion has demonstrated considerable potential in initial studies. Its feasibility, low emissions, and possible cost-effectiveness make it a compelling area for further investigation. Encouraging deeper research and development into such innovative technologies could diversify the portfolio of sustainable options available for the maritime industry and accelerate the transition toward cleaner and more resilient propulsion systems.

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