A Decade of Organic Rankine Cycle Research Trends and Evolution: A Bibliometric Analysis

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Abstract: Since 2000, Organic Rankine Cycles (ORC) research has experienced a surge in interest, driven by the growing need to recover low-to-medium temperature heat. However, there is a lack of research on trends and science mapping in this field. This study aims to address this gap by conducting a bibliometric analysis of ORC research from 2013 to 2023. Data were gathered from Scopus and Web of Science (WoS) databases until early 2023, ensuring data quality and relevance through filters for publication year, document type, language, and subject area. The analysis utilized Biblioshiny software to manage and interpret the extensive dataset efficiently. The analysis revealed 2,462 articles published during this period, with 3,753 authors from 1,860 institutions in 77 countries. The top five contributing countries were China, the United Kingdom, Iran, and several European countries. The most influential journal was "Energy"; the most prolific author, Zhang H. Tianjin University**,** made the most significant contribution to ORC research. Furthermore, the thematic analysis identified optimization, waste heat recovery, and zeotropic mixture as motor themes in ORC research. Emerging technologies such as machine learning for system optimization and energy storage integration were also highlighted. The supercritical cycle type was the most widely used concept in the last decade. Additionally, there was a growing interest in recuperative and regenerative ORCs, reflecting advancements in heat exchanger integration and preheating techniques. The study's findings provide a comprehensive overview of ORC trends and offer proposals for future research. It also pioneers a novel approach in ORC bibliometric research by integrating data from two major databases.

Keywords: organic Rankine cycle; bibliometric; renewable energy; energy conservation; waste-to-energy

1. Introduction

Interest in Organic Rankine Cycles (ORC) is growing in generating usable energy from renewable sources, industrial waste heat, and fuel cells[1–3]. This thermodynamic process converts low-temperature waste heat into alternative energy, providing a sustainable solution to meet energy demands[4]. By leveraging underutilized thermal energy sources, ORC technology can mitigate emissions, decrease reliance on fossil fuels, and promote a more sustainable energy sector [5–7].

Research work in this field is remarkably diverse, encompassing working fluid selection, performance evaluation, and economic and thermal analyses of ORCs [8–12]. Another major research focus is the design and optimization of ORC components[13–15]. Simulation, modeling, and experimental studies are also conducted to improve ORC efficiency and performance[16–18].

Existing reviews of ORC literature have been conducted, but most have been limited to specific aspects of the technology. For instance, some reviews have focused on the advancements in machine learning applications for designing and optimizing ORC systems[19], while others have analyzed the energy sources used in ORC systems[20–23]. In contrast, some studies have explored the ORC power systems[24–26], while others have focused on the applications of ORC in small-scale systems[27] or internal combustion engines[28,29].

Despite the significant progress in ORC research, there is a surprising lack of discussion on research trends and the evolution of studies in this field. A bibliometric analysis is crucial to fill this gap, as it helps to understand the research landscape, identify patterns and trends, and evaluate research impact[30]. This analysis enables researchers to inform their research decisions, identify potential collaborators, evaluate the quality of their work, and gain a comprehensive understanding of the scientific landscape that informs research priorities and drives innovation.

One notable study evaluated the global trends in ORC research from 2000 to 2016, examining the geographical distribution of authors and institutions, compiling lists of authors, institutions, and their contributions to journals, and analyzing citations and authorship patterns[31]. However, this analysis was insufficient to fully capture the trends and scientific mapping in ORC literature, as it only scratched the surface of the complex research landscape. To gain a more comprehensive understanding of the field, we propose combining three additional analytical methods: co-citation analysis, bibliometric coupling, and thematic analysis.

Co-citation analysis plays a crucial role in examining the structure of a research topic, as it reveals the interconnections among authors, journals, titles, and keywords[32]. Co-citation analysis identifies the relationships between documents by examining how frequently pairs of documents are cited together by subsequent research. A bibliometric coupling analysis has been utilized to identify potential research topics by categorizing and clustering scientific articles within a dataset[33]. Unlike co-citation analysis, which focuses on past citations, bibliometric coupling looks at the shared references of contemporary documents, thus identifying current research fronts and emerging trends. Additionally, thematic analysis can be applied to explore further the themes and patterns emerging from these relationships, providing a more comprehensive understanding of the research landscape[30]. According to Donthu et al.[30] and Phan Than[34], combining these methods can help gain a deeper understanding of research topics and track the evolution and connections of research ideas over time. This approach also comprehensively overviews the field's trends, structures, and knowledge development.

A similar study was conducted on literature from the ORC field between 2010 and 2020, utilizing co-citation analysis to examine the relationships between various publications[21]. However, this study focuses on solar-powered ORC research, differentiating it from the broader ORC literature. As a result, this study cannot provide a comprehensive overview of research trends and developments in the ORC field, as it is limited to a specific subset of research.

Both studies relied exclusively on the Scopus database for data collection. Although Scopus has a broader publication coverage, including more journals and articles, and provides better coverage of publications from developing countries, it has limitations regarding accuracy[35,36]. Some researchers recommend combining it with the WoS database to obtain a more comprehensive overview of the research literature[36–38]. WoS has advantages in terms of coverage across years and offers a varied range of information, thereby enhancing the accuracy of the databases that will be analyzed[36]. By harnessing the strengths of WoS in terms of quality and coverage, as well as the strengths of Scopus in terms of quantity and diversity, researchers can gain a more nuanced understanding of the research landscape.

Based on the explanation, the current research landscape in ORC is characterized by the following critical gaps:

- Lack of comprehensive trends: Despite the passage of ten years, from 2013 to 2023, there is a scarcity of studies that comprehensively examine the trends in ORC research.
- Limited scope of analysis: The existing analysis is often restricted to a single database, which may not provide a comprehensive understanding of the ORC research landscape.
- Insufficient knowledge structure analysis: A thorough analysis of the knowledge structure and potential research topics in ORC has yet to be conducted, mainly through co-citation analysis, bibliometric coupling, and thematic mapping.

Therefore, this study aims to provide a comprehensive overview of the research landscape in ORC over the past decade to fill the existing research gaps. To achieve this, we will thoroughly analyze ORC literature, combining Scopus and Web of Science databases to obtain a more comprehensive picture. Our research objectives are as follows:

- Analyze publication development, including top papers, author contributions, sources, and keywords; author productivity; keywords co-occurrence analysis; country and affiliation contributions; and network analysis.
- Investigate the knowledge structures of ORC (intellectual, social, and conceptual) through co-citation analysis, bibliometric coupling, thematic analysis, and co-authorship collaboration network.
- Analyze the research trend and knowledge development of ORC.
- Map out future issues and research directions for ORC.

The study's findings on ORC research have significant implications across policy, industry, and future research. Policymakers can use global research insights to target funding and incentives, focusing on optimizing working fluids and component design to accelerate ORC technology deployment and meet sustainability goals. For industry, trends like advancements in waste heat recovery and new working fluids provide opportunities for innovation and market expansion, facilitating technology transfer and global market penetration. Future research should prioritize efficient, environmentally friendly working fluids and integrate ORC systems with renewables like solar PV and wind to enhance scalability and performance. Emphasizing AI for real-time optimization, thermoeconomic analyses, and rigorous experimental validation of modeling techniques are also crucial for advancing ORC technology and achieving sustainable energy solutions globally.

The paper is structured into five sections. The first section provides an introduction, setting the paper's stage. The second section offers a brief overview of the Organic Rankine Cycle, providing a solid foundation for the research. Section 3 outlines the research methods, detailing the approach taken. Section 4 presents the results and ensuing discussions, providing insight into the findings. The concluding section, Section 5, summarizes the paper with final remarks, leaving the reader with a clear understanding of the main points.

2. Organic Rankine cycle

2.1 ORC working principle and applications

The Organic Rankine Cycle shares similarities with the Steam Rankine Cycle in its vaporization and expansion processes. However, it differs in its working fluid, an organic compound with a lower boiling point than water. It allows ORC to generate power from low-temperature heat sources, making it an attractive option for decentralized energy applications.

The ORC system consists of four main components: an evaporator, expander, condenser, and pump (Fig. 1(a))[39,40]. According to Zhang et al.[39], the evaporator optimizes heat from an external source at a temperature range of 150–350°C (such as industrial waste heat, geothermal energy, solar thermal energy, or biomass) to the organic working fluid, causing it to vaporize. The working fluid selection depends on several factors, including thermo-physical properties, safety and environmental conditions, critical temperatures, flow rates and pressures, the sizes of turbines and other system components, and the cycle configurations. Application of R1234ze for a supercritical-subcritical ORC has been analyzed to obtain exergy efficiency up to 61.25%[41].

The high-pressure vapor is then expanded in the expander (typically a turbine), which converts thermal energy into mechanical work to drive a generator. A radial inflow turbine has been recently designed to increase the ORC system performance with its isentropic performance up to 88.57 %[42]. Then, the condenser cools the working fluid, causing it to return to its liquid state while transferring the remaining heat to a cooling medium, such as air or water. Verma et al. reported that the working fluid's mass flow rate and mass velocity significantly impact condenser performance, while channel distance and width have less impact[43]. The working fluid has low pressure when coming out from the condenser outlet. Therefore, the pump increases the pressure of the condensed working fluid and recirculates it back to the evaporator, enabling continuous operation. The thermodynamic cycle of the ORC system can be depicted in a T-S diagram, as shown in Fig. 1(b)[39].

The ORC technology utilization extends across various renewable energy applications, each with distinct heat sources and operational considerations. In industrial waste heat recovery (WHR), experimental studies have aimed to enhance system efficiency and explore the potential for cogeneration, including heating, cooling, freshwater production, and electricity generation[44]. Furthermore, integrating ORCs in waste heat recovery from truck engines, particularly heavy-duty ones, has garnered attention due to their substantial waste heat potential and the imperative to reduce emissions in the transport sector[45]. The ORC system recovers waste heat from truck engines with net power outputs of 1.8-9.6 kW and 1.0-7.8 kW when using cyclopentane and ethanol, respectively[45].

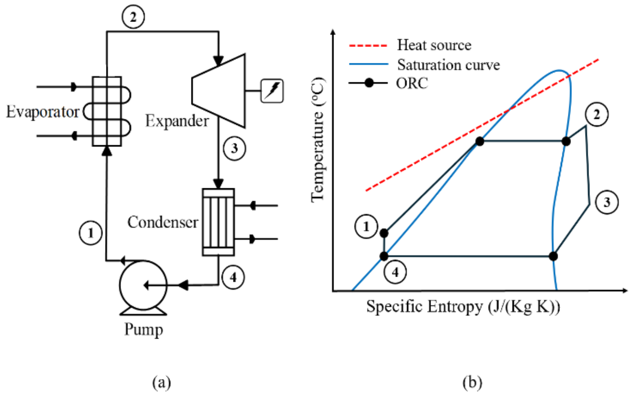

Fig.1: Organic Rankine Cycle schematic view.

The application of ORCs in the maritime sector for large vessels and their potential to enhance overall energy efficiency underscore their relevance in diverse settings[46]. Numerical studies on Wartsila 12V46F engines reveal that the highest energy recovery comes from scavenging air cooling systems. Despite practical implementation constraints, the optimal ORC structures achieve a WHR system efficiency of 15%[47]. Geothermal energy, particularly for temperatures below 180°C, represents another prominent application area for ORCs, with ongoing efforts to improve condensation concepts and explore tri- or polygeneration plant configurations[48]. Geothermal power plants are not economical for temperatures below 80°C due to low system efficiency and high component power consumption, such as pumps consuming up to 50% of generated power[49].

Although facing competition from low-cost photovoltaic modules, solar energy remains a promising heat source for ORCs, especially in small-scale power generation and cogeneration applications[50]. With solar irradiance of 5.5 kWh/m²/day, the ORC system employing working fluids R245fa, R11, and R123 indicated a maximum system efficiency of 6.8%, with power outputs reaching 380 MW at temperatures of 90–120°C[51]. Beyond these, other potential heat sources, including waste incineration plants, biomass plants, liquefied natural gas (LNG), and outer space applications, highlight ORC technology's versatility and expanding domains in the renewable energy landscape[52].

2.2 Advanced ORC architectures advantages, challenges, and recent research

The layout of the ORC is relatively more straightforward than its steam counterpart, characterized by a single heat exchanger performing three evaporation phases: preheating, vaporization, and superheating. Various advanced ORC architectures have been explored to provide opportunities to enhance the efficiency and performance of ORCs for different applications. These advanced architectures, including transcritical, supercritical, the ORC with recuperator (RC), regenerative ORC (RG), organic flash cycle (OFC), trilateral cycle (TLC), transcritical cycle (TCC), and ORC with multiple evaporation pressures (MP)[53]. However, they each come with their unique set of challenges.

Transcritical ORCs

Transcritical ORCs offer significant advantages, such as improved thermal efficiency and effectiveness for low-temperature heat sources. However, they face challenges related to high pressures and temperatures required for operation, which can lead to increased material stresses and potential safety concerns. Additionally, efficiency drops at partial load conditions present further difficulties. Key challenges include screening zeotropic mixtures, designing vapor generators for supercritical fluids, and precisely controlling two-phase flows. Potential solutions and ongoing research focus on developing comprehensive selection criteria for zeotropic mixtures as working fluids[54] and creating a robust selection framework that incorporates thermodynamic and thermo-economic analysis[55]. Innovations such as ejector-based transcritical regenerative series two-stage ORCs[56], and implementations for biodiesel internal combustion engines[57], marine engines[58], and geothermal single flash applications[59] are being explored. Further, thermo-environmental analysis, performance optimization[60], and multifactor evaluation are essential for improving the feasibility and efficiency of transcritical ORCs.

Supercritical ORCs

Supercritical ORCs offer advantages such as higher efficiencies and improved heat transfer characteristics. However, they require precise control over supercritical conditions to avoid inefficiencies and system instabilities. The challenges include high capital costs due to the need for specialized equipment capable of handling supercritical fluids, optimization of power output and thermal efficiency, and selecting the appropriate organic fluid. Potential solutions and ongoing research focus on multi-optimization methods such as NSGA-II, TOPSIS, and Shannon Entropy[61]. Innovations include cascade systems consisting of a supercritical CO_2 cycle and an ORC[62], low-temperature multi-effect desalination coupled with mechanical vapor compression[63], and comprehensive thermodynamic and exergoeconomic analysis[64]. Additional research areas include the selection of working fluids[65], coupling supercritical ORCs with vapor-compression refrigeration cycles[66], thermo-economical optimization[41], and studying the thermal stability of HFO-1234ze(E) as a working fluid[67].

Recuperative ORCs

Recuperative Organic Rankine Cycles (ORCs) enhance efficiency and reduce the thermal load on the heat source. However, these systems encounter challenges related to the intricate design and integration of internal heat exchangers. There is a risk of increased pressure drops, which can lower overall system efficiency. Moreover, the systems become more complex and costly, necessitating precise control over heat flow. Additionally, balancing the temperature and flow rates, along with the selection of appropriate working fluids, pose significant challenges. Potential solutions and ongoing research focus on utilizing three-fluid wound tube heat exchangers and implementing advanced thermal management strategies, including high-efficiency cooling systems and optimizing coolant circulation rates[68]. Studies have shown that Benzene fluid in a recuperative ORC performs better than Cyclohexane, Toluene, and n-hexane fluids[69].

Supercritical CO_2 ORCs

Supercritical CO_2 ORCs offer high efficiencies and lower environmental impact. However, they face challenges such as the need for high-pressure components, material compatibility issues with CO_2, and the necessity for precise control of CO_2's thermodynamic properties for optimal performance. Performance optimization remains a significant challenge. Potential solutions and ongoing research focus on implementing cascade systems that combine a supercritical CO_2 cycle with either subcritical or transcritical ORCs, as utilizing R1233zd(E) provides a better thermal match and performance[62]. Multi-objective analysis and optimization[70], recompression, reheat, and pressurized intercooling S-CO_2 systems[70], and the implementation of supercritical carbon dioxide recompression Brayton cycles (SCRBC) coupled with ORC[71]are being explored. Additionally, performing detailed thermodynamic and economic assessments on combined supercritical CO_2 with ORC systems is also a key area of research[72].

Regenerative ORCs

Regenerative ORCs have the advantage of significantly enhancing the system's thermal efficiency, reducing total irreversibility, improving second-law efficiency, and reducing fuel consumption. However, these systems face challenges due to the added complexity and cost of additional components and the need for parametric optimization. Potential solutions and ongoing research include the use of super dry working fluids such as heptane, pentane, hexane, propylcyclohexane, undecane, and o-xylene[73], the application of particle swarm optimization techniques[74], and the insertion of a feed heater after the condenser and turbine[75]. Further optimization of the evaporator heat transfer area, mass flow rate, and superheat can be achieved by employing classical and finite thermodynamic approaches[76].

Multi-stage ORCs

Multi-stage ORCs offer enhanced efficiency and better adaptation to varying heat source conditions. However, they face challenges such as increased mechanical complexity and cost, the need for precise control of two-phase flows, and the selection of appropriate working fluids. Potential solutions and ongoing research include implementing transcritical ejector regenerative series two-stage ORCs, which replace the need for two-phase flows with vapor-vapor regeneration via an ejector operating entirely with fully evaporated vapor[56]. Additionally, the evaluation of 17 working fluids has shown that R1234yf, propane, R1234ze, and R152a (high temperature) exhibit excellent maximum net power output[77]. Exergoeconomic evaluation of these working fluids further supports their potential[78], and implementing a transcritical-recuperative design can eliminate vapor extraction, allowing for direct integration of compact two-stage turbines[79].

Reversible Heat Pump ORCs

Reversible Heat Pump ORC architecture boasts the advantages of dual functionality, allowing for both heating and power generation, thereby increasing system flexibility. However, it faces challenges such as complex control mechanisms, higher initial investment, selection of appropriate working fluids, and complexities in steady-state measurement during thermodynamic cycle analysis. Potential solutions and ongoing research include thermoeconomic analysis and multi-objective optimization to enhance system performance and cost-effectiveness[80]. Investigations into four working fluids have highlighted R1233zd(E) as a suitable choice due to its ability to enable a design without expensive vacuum sealing and to reduce the required size of the internal heat exchanger[81]. Additionally, implementing reconciliation methods to close energy and mass balances and determine unknown parameters precisely can address measurement challenges[82].

Flash ORCs

Flash ORC architecture offers high efficiency, especially for low-temperature heat sources. However, it faces challenges such as the need for precise control of the flashing process, increased system complexity, and unclear economic performance and investment costs. Potential solutions and ongoing research include combining incomplete evaporation and flash evaporation strategies in single and double flash cycle systems[83], performing comprehensive thermodynamic and economic analyses to understand better and improve system viability[84], incorporating flash ORC to recover hydrothermal carbonization slurry product[85], and integrating ORC with ejector refrigeration cycle systems using zeotropic mixtures to enhance performance[86].

Trilateral ORCs

Trilateral ORC architecture offers enhanced efficiency and a simplified design for low-temperature applications. However, it faces challenges such as precise control of phase transition, lower first-law efficiency, management of saturated liquid states, and matching performance between the heat source and working fluid. Potential solutions and ongoing research include combining a trilateral cycle with an ORC employing four fluids, where toluene outperformed cyclohexane, benzene, and water[87], using genetic algorithms to optimize system performance[88], and developing a cascade cycle that combines a trilateral cycle with an ORC to improve temperature matching between the working fluid and heat source by using toluene[89].

Partial Evaporation ORCs

The Partial Evaporation ORC (PE-ORC) achieves up to 80% higher exergy efficiency compared to the conventional ORC due to its better heat source utilization, particularly with vapor qualities in the range of 20% to 40%[90,91]. By partially evaporating the working fluid, PE-ORC more effectively matches the temperature profiles of the heat source and working fluid, enhancing efficiency and expanding the potential for economically exploiting low-temperature heat sources like solar thermal energy and industrial waste heat[91]. Low-GWP refrigerant R1233zd(E) further reduces environmental impact[90]. However, challenges include optimizing ORC structures, adapting to variable heat source temperatures, and addressing the long-term effects of the two-phase operation on expansion devices like twin-screw expanders[90,91]. The study identifies optimized design parameters and suggests using coupled tools (EES and TRNSYS) for accurate dynamic analysis[90]. Future research should focus on the long-term viability, economic feasibility, and integration of PE-ORC with other renewable energy sources and waste heat recovery systems, as well as the development of critical components like expanders and pumps[91]. A comprehensive investigation into economic, environmental, and technical aspects will enhance understanding of the system's potential and challenges [90].

3. Method

The study conducted a quantitative bibliometric analysis to explore the ORC field comprehensively. It addresses the limitations inherent in qualitative methodologies, particularly in systematic literature reviews, where the influence of researchers' backgrounds can impact the outcomes[92]. Bibliometrics entails the statistical analysis of scientific articles in a field[93,94]. This approach enables researchers to navigate data across diverse databases[30], offering extensive perspectives. It aids in unveiling evolutionary trends, pinpointing knowledge gaps, fostering innovative ideas, and situating research within the context of the discussed area[95].

3.1 Data collection

Our data collection process consisted of four distinct stages: (1) identification of relevant scientific articles, (2) filtering of records, (3) screening of records, and (4) merging and deleting duplicate records (see Fig. 2). The following describes each stage in detail:

Identification scientific articles

We sourced scientific articles on ORC from two leading online databases, Scopus and Web of Science. Scopus and Web of Science are comprehensive databases that systematically index peer-reviewed journals and conference proceedings relevant to ORC. Their indexing policies ensure that a wide range of high-quality literature is included, which is crucial for researchers seeking authoritative information. Our selection was guided by the insights of Muhuri et al.[96] and Pranckutė[97], who highlighted the importance of reputable publishers and significant citation databases. We focused on publications from established publishers such as Emerald, Elsevier, Springer, Inderscience, and Taylor and Francis Group to ensure robust data sources. Building on the observations of Echchakoui [36], these databases contribute to a comprehensive understanding, enriching our study with diverse perspectives.

To ensure a focused and precise search, we used a single keyword, "organic Rankine cycle," and conducted the search using the query outlined in Tables 1 and 2. The search yielded 3,018 records in Scopus and 1,489 in Web of Science, resulting in a total of 4,507 records for further analysis in this study.

Records filtering

To ensure the quality of our data, we applied specific filters to the records. We limited our search to scientific articles published between 2013 and mid-2023, which allowed us to capture research articles on ORC from the last decade. We restricted our search to journal articles and conference proceedings, which undergo thorough peer review and revision. Only the final versions of records were included to ensure content accuracy without further modifications. We also applied an English language restriction to facilitate researchers' comprehension based on their language proficiency. The application of database features for filtering resulted in 3,700 qualifying records, with 2,355 sourced from Scopus and 1,345 from WoS.

Merging and Deleting Duplicate Records

Given that we retrieved records from Scopus and WoS, we combined the search results to mitigate potential duplications. We then applied a duplicate removal procedure using Rstudio, as outlined by Echchakoui [36]. After this process, 1,238 records were excluded, leaving a final dataset of 2,462 records for detailed analysis.

Record Assessment for Including

The final stage involved assessing the records to identify those that meet our inclusion criteria. We employed a screening method outlined by Dohale et al.[93] to review the records. We evaluated each record based on its relevance to ORC, methodology, and empirical findings. Records that did not meet our criteria were excluded from further analysis. The assessment process resulted in a final dataset of 2,462 records aligned with our established criteria.

3.2 Tool and Data Analysis

This study employed a rigorous bibliometric analysis using Biblioshiny, a cutting-edge application that enabled performance evaluation, science mapping, and network analysis[98]. Our choice of tool was guided by its demonstrated efficacy in managing merged data sources, as highlighted by Echchakoui[36]. Following the approach outlined by Donthu et al.[30], we analyzed a dataset comprising 2,462 documents to uncover trends, key indicators, and community structures, as well as identified actors and network models in specific relationships. The workflow is illustrated in Fig. 3.

In this study, various techniques in the Biblioshiny are employed to uncover trends and growth patterns, understand intellectual and social structures, and explore conceptual connections within ORC research fields. Trends and growth analysis involves tracking the publication output over time to identify emerging topics and shifts in the research focus. Network analysis visualizes relationships between entities like authors, keywords, or publications, revealing collaborative networks (co-authorship), citation patterns (co-citation analysis), and thematic clusters (keyword co-occurrence). Citation analysis assesses the impact of publications through citation counts, while co-citation and bibliometric coupling analyses identify intellectual structures by examining shared citations and common bibliographic references, respectively. Social structure analysis examines the collaborative networks and institutional affiliations of authors. Thematic analysis, part of conceptual structure exploration, categorizes and maps the underlying themes and concepts in the literature, providing insights into the intellectual landscape and evolution of research domains.

The Biblioshiny generally provides the analysis result in a table and plot format. We can save them in .xlsx or .png files. The Biblioshiny generates various visualization methods to help researchers explore and understand bibliographic data, such as temporal trends, performance indicators (bar charts and tables), network graphs, and cluster maps.

Table 1. Data assortment steps of Scopus.

Steps	Question on Scopus	Description	Count
1.	TITLE-ABS-KEY	(TITLE ("organic Rankine cycle") AND ABS ("organic Rankine cycle") AND KEY ("organic Rankine cycle"))	3,018
2.	AND (LIMIT-TO)	(PUBYEAR, "2023", "2022", "2021", "2020, "2019", "2018", "2017", "2016", "2015", "2014", "2013")	2,704

Steps	Question on Scopus	Description	Count
3.	AND (LIMIT-TO)	(DOCTYPE, "article", "conference paper")	2,590
4.	AND (LIMIT-TO)	(PUBSTAGE, "final")	2,572
5.	AND (LIMIT-TO)	(SRCTYPE, "journal", "conference proc")	2,355
6.	AND (LIMIT-TO)	(LANGUAGE, "English")	2,355

Table 2. Data assortment steps of WoS.

Steps	Question on Web of Science	Description	Count
1.	Title AND Abstract AND Author Keywords	(TI= ("organic Rankine cycle") AND AB= ("organic Rankine cycle") AND AK= ("organic Rankine cycle"))	1,489
2.	AND (Refined By)	Publication Years: 2023 or 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 or 2014 or 2013	1,391
3.	AND (Refined By)	Document Types: Article or Proceeding Paper	1,353
4.	AND (Refined By)	Languages: English	1,345

4. Result and discussion

4.1 Publication trend

In recent years, ORC has emerged as a significant concern, primarily employed to address the demand for new and renewable energy sources. Table 3 summarizes the bibliometric metadata of ORC for the past decade (2013-2023), which includes 3,753 authors and 2,461 documents. Notably, the publication rate of ORC-related research has experienced a significant surge in recent years, with an average annual growth rate of 2.94% and a mean citation rate of 23.3 per year per document.

The analysis reveals that 2017 and 2020 were notable years for ORC publications, with 1,163 articles published in these two years alone, accounting for approximately 47.26% of all articles published in the last decade. Furthermore, the annual scientific publications distribution analysis shows that the highest productivity was achieved in 2020, with 309 papers (refer to Fig. 4). The decline in productivity observed in subsequent years might be attributed to the emergence of the COVID-19 pandemic. The COVID-19 pandemic profoundly impacted global research activities from 2020 to 2021, causing delays and interruptions due to lockdowns and economic disruptions. Many research institutions and laboratories temporarily closed or reduced operations, affecting ongoing projects, including those in ORC research[99,100].

In addition to publication counts, an analysis of citation rates from 2013 to 2023 (refer to Fig. 5) reveals that research published from 2013-2015 had a high impact, with an average citation rate above 4.0, indicating frequent referencing. Despite a substantial increase in publications from 2016-2020, citation rates slightly declined to around 3.5, suggesting a decrease in the average influence of individual papers. A more noticeable decline occurred from 2021-2023, particularly in 2023, with a rate of 0.55, likely due to the recentness of these publications. This trend highlights the need for future research to focus on increasing publication quantity and enhancing quality and relevance.

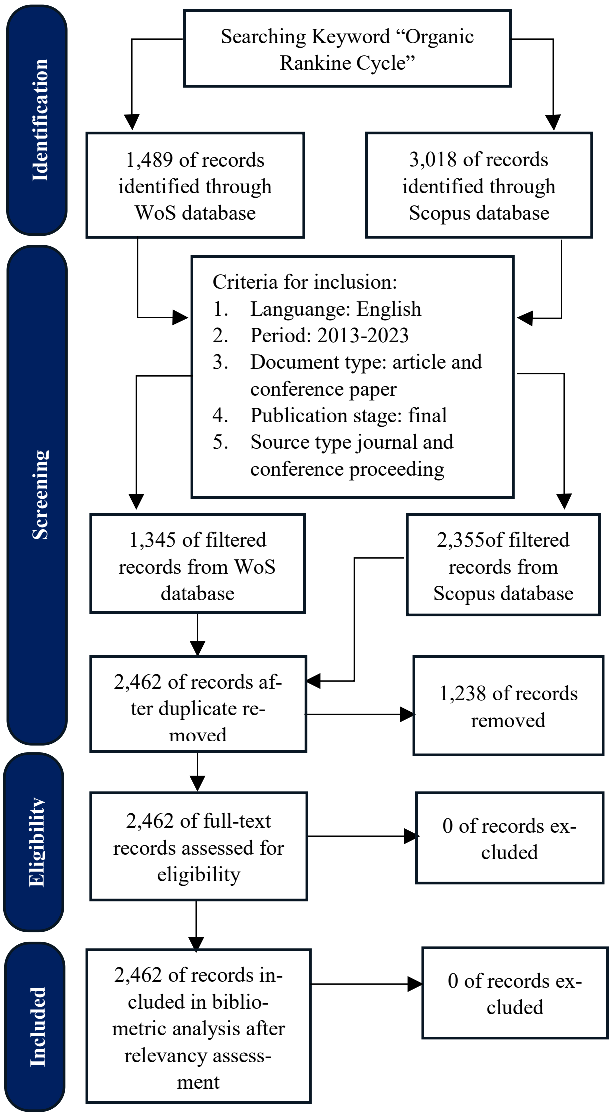

Fig. 2: PRISMA flowchart of ORC bibliometric review.

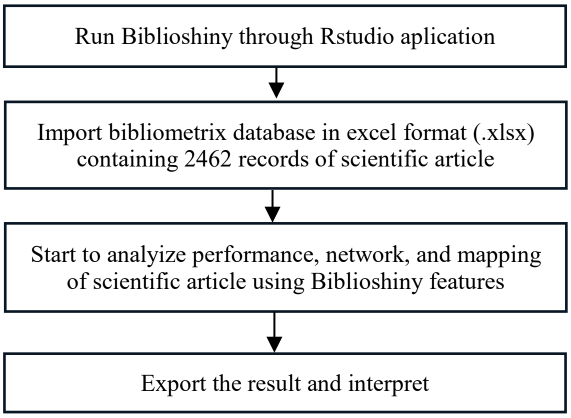

Fig. 3: Flowchart of bibliometric analysis using Biblioshiny.

Table 3. Statistics of the collected articles.

Description	**Results**
Timespan	2013:2023
Sources (Journals, Books, etc)	471
Documents	2462
Annual Growth Rate %	2.94
Document Average Age	4.65
Average citations per doc	23.3
References	52313
Keywords Plus (ID)	5256
Author's Keywords (DE)	3892
Authors	3753

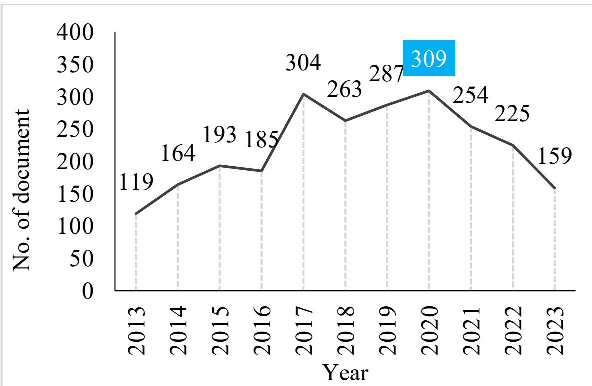

Fig.4: ORC publication trend.

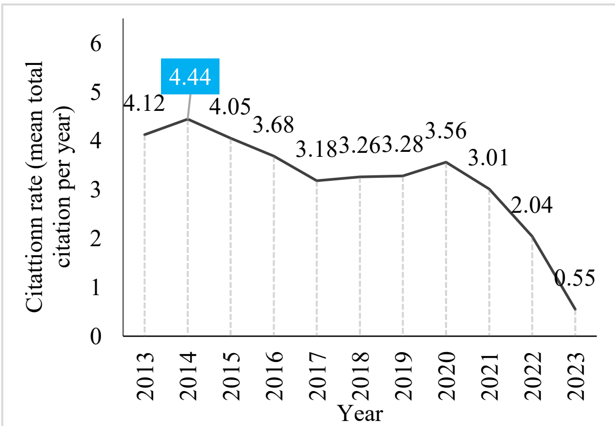

Fig. 5: ORC publication citation rate

4.2 Top author, author productivity, and network analysis

Fig. 6 analyses the top three productive authors in ORC, with 3,753 authors and 2,462 documents published over the past decade. Zhang H, Zhang Y, and Yang F are the most prolific authors, with 87, 68, and 68 publications, respectively. Their significant contributions to ORC research underscore their impact on the field. The H-index, G-index, and TC (Total Citations) are critical metrics in evaluating an author's influence and productivity. For instance, Zhang H stands out as the most influential author with a high H-index (25), G-index (46), and TC (2,349) metrics. The H-index indicates that Zhang H has at least 25 publications that have each been cited 25 times or more, signifying sustained and significant impact over time. A high H-index combined with substantial TC suggests that the author's work is prolific and consistently referenced by peers, indicating enduring relevance and influence in the field. However, the M-index, which considers an author's career length, ranks Zhang H sixth. This discrepancy is due to the M-index's calculation, which divides the H-index by the number of years the author has been active in publishing. Therefore, authors with longer careers may have lower M-indices despite their overall influence[101].

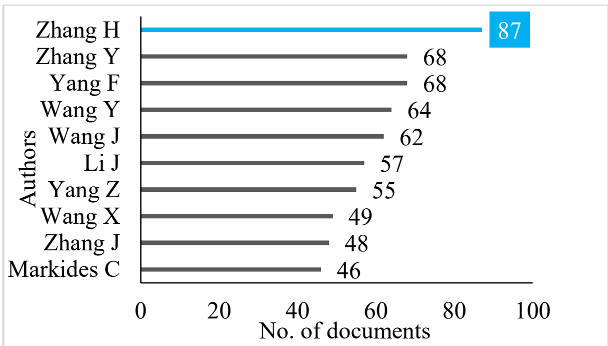

Fig. 6: Most relevant author.

In contrast, Xing C stands out as the author with the highest M-index at 3.5, surpassing Zhang G (M-Index = 2.273) and Zhang Y (M-Index = 2). This highlights Xing C's potential as a prominent figure in ORC literature. The disparity between Zhang H's M-index and Xing C's M-index underscores the importance of considering multiple metrics when evaluating an author's influence.

Table 4 details the top 10 most productive authors based on various indices. This multi-metric approach underscores the importance of considering different aspects of an author's contributions, from their sustained impact (H-index) to their overall influence (TC) and productivity relative to career length (M-index).

4.3 Top paper

Identifying critical contributions in ORC literature is essential for tracking research progress. An analysis of citation trends provides valuable insights into the direction of research. Our study examined 2,461 documents, with 57,364 citations, averaging 23.3 citations per document. The top 10 most globally cited papers account for 4.1% of all citations, primarily published between 2013 and 2015. Fig. 7 presents the top 10 globally cited documents, with Colonna P.[25] being the most influential, with 302 citations at an average of 30.2 per year. This high citation count indicates that Colonna P.'s work has had a substantial and lasting impact on the field. Other notable papers are by Declaye S.[102], Khaljani M.[103], Maraver D.[104], and Akbari AD.[105] are in the second to fourth positions with TLC scores of 245, 241, 240, and 238, respectively.

Table 4. Top 10 most productive authors based on H-Index, G-Index, TC Index, and NP.

Authors	H- Index	G-Index	M- Index	TC	NP
Zhang H	25	46	2.273	2,349	87
Li J	24	37	2.182	1,462	57
Wang J	24	44	2.182	1,988	62
Markides C	23	43	2.3	1,860	46
Wang X	23	40	2.091	1,655	49
Yang F	23	43	2.091	2,028	68
Yang Z	22	38	2	1,525	55
Liu C	21	36	1.909	1,347	43
Duan Y	20	32	1.818	1,401	32
Shu G	20	40	1.818	1,768	40

*TC = total citations; NP = number of publications

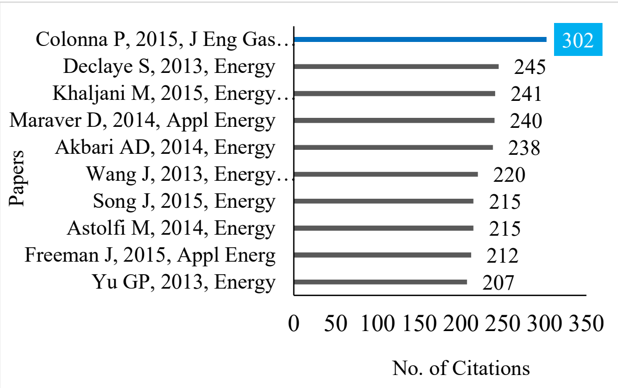

Fig. 7: Most globally cited paper.

4.4 Countries' contribution, affiliation contribution, and network analysis

Fig. 8 illustrates the global scope of ORC research, with a presence in 74 countries. Notably, China, Iran, and the United Kingdom emerged as prominent contributors, with substantial citation impact. These three nations account for 29,419 citations, representing 53.4% of 54,995 global citations. The global reach of ORC research is evident in Fig.8.

Fig. 10 presents a visual representation of the intricate network of collaborative relationships among countries, with the thickness of connecting lines indicating the strength of these affiliations. The partnership between China and the United Kingdom stands out for its remarkable global cooperation and closely-knit collaboration. These two nations also lead in terms of collaborations with other countries.

Shifting to affiliations and network analysis, Fig. 9 and Fig. 11 provide valuable insight into the leading academic entities in this field. Fig. 8 uses the co-authorship index per document to reflect the collaborative nature of scientific work. The result highlights Tianjin University, Beijing University of Technology, and North China as prominent contributors in the ORC domain. These findings underscore the collaborative strengths and key affiliations shaping the landscape of ORC research.

Based on Fig. 11, Tianjin University has the most extensive collaborative network within China, while the Technical University of Denmark has the most extensive network regarding international inter-institutional collaboration. The Technical University of Denmark collaborates with Beijing University of Technology (China), Brunei University (Brunei Darussalam), the University of Liege (Belgium), and the University of Padova (Italy). This nuanced analysis reveals the intricate web of collaborations, highlighting Tianjin University's domestic influence and the Technical University of Denmark's global outreach in ORC research.

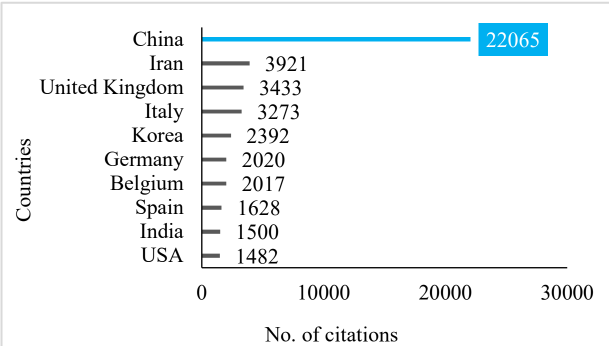

Fig. 8: Most Cited Countries.

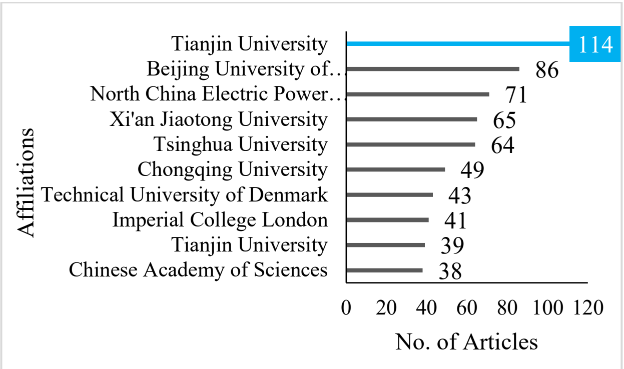

Fig. 9: Most Relevant Affiliations.

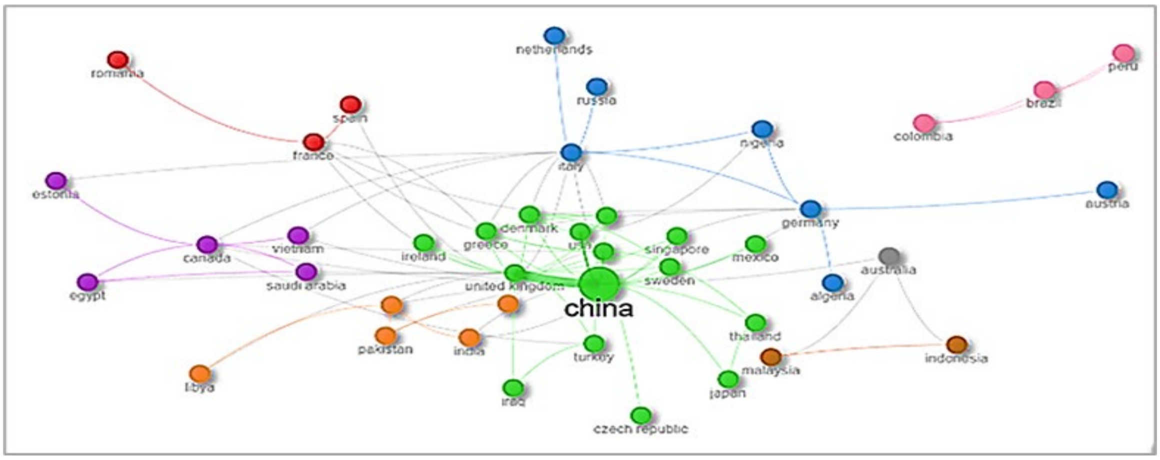

Fig. 10: Countries collaboration Network.

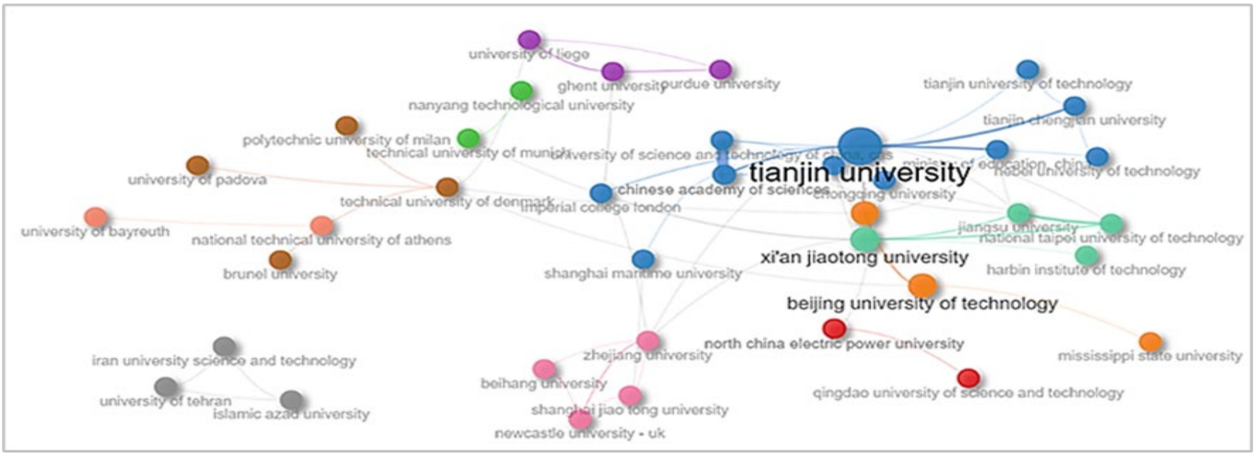

Fig. 11: Affiliation collaboration network.

4.5 Top sources and citation analysis

The analysis of Table 5 reveals the top 10 most influential in the ORC literature. According to Bradford's law, these journals cluster into the nucleus zone, characterized by the highest productivity level over time[106]. "Energy" is the leading journal, with 344 publications in the last decade. "Energy Conversion and Management" and "Applied Thermal Engineering" are closely behind, demonstrating exceptional impact in the field.

The top three journals exhibit the highest values for H-Index, G-Index, M-Index, and Total Citation (TC) Index among the top 10 sources listed in Table 6. "Energy" stands out with an H-Index of 64, a G-Index of 95, and an M-Index of 5.818. Moreover, it boasts the highest number of citations, totaling 13,500 TC. This analysis highlights the crucial role of these journals in shaping and advancing ORC research. Their influence is reflected in their publications' frequency and quality and impact on the broader research landscape.

4.6 Top keyword and keyword co-occurrence analysis

The keyword analysis results, illustrated in Fig. 12, reveal a striking thematic concentration. The term "organic Rankine cycle" emerged as the most frequently used keyword, appearing an impressive 1,957 times. In second and third place are "waste heat recovery" and "working fluid," with respective frequencies of 433 and 149. These findings provide valuable insights into the predominant focus areas within ORC research, highlighting the significance of the organic Rankine cycle, waste heat recovery, and the importance of working fluid considerations in current studies.

This analysis not only identifies the core themes but also underscores their significance in the current landscape of ORC research. Moreover, the results demonstrate the interconnectedness of these themes, showcasing the complex relationships between key concepts in ORC research.

Fig. 13 illustrates the co-occurrence analysis results, which reveal three thematic clusters: "organic Rankine cycle," "waste heat recovery," and "working fluid." The primary cluster focuses on the "organic Rankine cycle," encompassing keywords such as exergy efficiency, waste heat, and others. The secondary cluster includes keywords like zeotropic mixture and performance analysis, while the third cluster involves keywords such as thermal efficiency and geothermal.

Table 5. Top 10 sources impact.

Sources	H Index	G Index	M Index	TC	NP	PY_start
Energy	64	95	5.8	13500	344	2013
Energy Conversion and Management	62	88	5.6	12678	303	2013
Applied Thermal Engineering	50	71	4.5	7447	216	2013
Applied Energy	49	77	4.4	6386	108	2013
Energies	24	37	2.4	2070	130	2014
Journal of Cleaner Production	24	36	3	1344	37	2016
Renewable Energy	21	33	1.9	1141	33	2013
Journal Of Engineering for Gas Turbines and Power	16	29	1.4	1046	29	2013
International Journal of Energy Research	13	19	1.2	435	32	2013
Energy Procedia	12	24	1.2	638	39	2014

*TC = total citations; NP = number of publications; PY_start = publication year_start

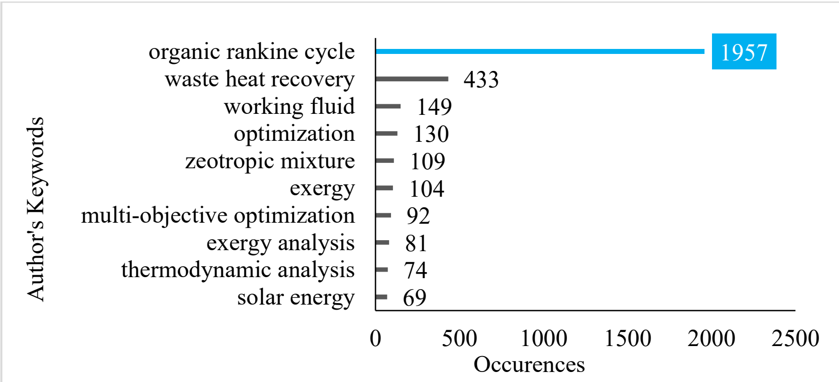

Fig.12: Most relevant keyword.

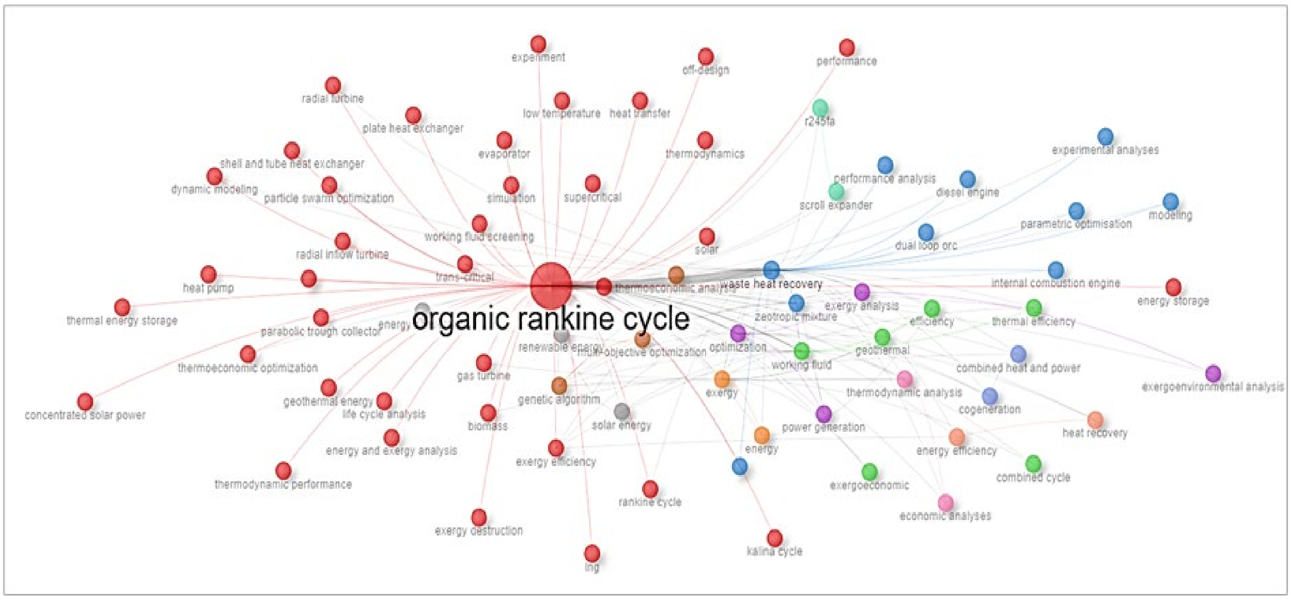

Fig.13: Keyword co-occurrence analysis.

4.7 Intellectual Structure

The intellectual structure of a research field can be elucidated by analyzing the authors, documents, or sources that exert significant influence in the academic domain[107]. Previous studies have consistently shown that co-citation and bibliographic coupling analyses can provide valuable insights into detecting intellectual structures[108]. Co-citation analysis reveals the foundational elements that underlie the field, while bibliometric coupling analysis highlights the current research fronts driving innovation[107].

4.7.1 Co-citation Analysis

Co-citation analysis is a crucial tool for understanding the intellectual evolution of ORC literature, as it examines the relationships among co-cited authors, documents, and sources, revealing the underlying knowledge structure of the field.[107].

The result of the co-citation analysis depicted in Fig. 14 reveals the presence of three distinct clusters of researchers, each contributing significantly to the ORC literature. The first cluster (in red) optimizes ORC by selecting suitable working fluids[27,40,53,109,110]. The second cluster (in blue) centers on designing and modeling turbines and scroll expanders in ORC[102,111–114]. The third cluster (in green) addresses evaluating the performance of organic fluids in ORC[115–119]. This detailed categorization provides a nuanced understanding of the diverse research themes and specialties within the ORC scholarly community.

4.7.2 Bibliometric Coupling Analysis

As defined by[120], bibliographic coupling refers to the phenomenon in academic literature where two distinct subsequent papers cite a single document concurrently. This simultaneous citation indicates a strong relationship between the two citing papers, subsequently increasing their likelihood of being cited by future publications. In this study, we conducted a coupling analysis at the document level, utilizing a dataset comprising 500 documents. The coupling strength was assessed based on references, while the impact was quantified using the local citation score.

The results of the bibliographic coupling analysis are visually presented in Fig.15, illustrating five distinct clusters organized by subject-relatedness. Each cluster's circles vary in size and color based on the typical number of citations among the selected documents. The largest cluster encompasses 167 items, followed by 106 items in the fourth cluster, 92 items in the third, 74 items in the second, and 47 items in the most minor (fifth) cluster. For a comprehensive analysis, only studies aligned with the thematic focus of each cluster have been included.

Cluster 1 explores ORC thermoeconomic analysis, a research area heavily influenced by[121–125]. Cluster 2 is a comprehensive repository of ORC optimization studies, primarily conducted by[126–130]. The third cluster is rooted in thermodynamic analysis and working fluid optimization for ORC, chiefly advanced by[131–134]. Cluster 4 addresses the working fluid selection method, as discussed by[135–138]. Lastly, the fifth cluster focuses on the experimental testing of ORC performance, primarily contributed by[17,139–145].

4.8 Social Structure

The social structure is revealed through a network analysis of co-authorship relationships[30]. This analysis, illustrated in Fig. 16, examines the co-occurrence of authors in ORC studies and uncovers complex social networks formed through collaborative research efforts[146]. Our investigation centered on ten authors who have published at least five papers together. Our findings show that academic connections are not limited to authors within the same country or institution but extend across geographical boundaries and national affiliations.

Fig. 16 reveals Zhang H as the most prominent collaborator in the ORC research network, with a notable volume of co-authored publications and collaborations. As a prominent figure in the network, Zhang H's collaborative endeavors span both domestic and international borders. While he has collaborated with numerous writers from his own country[147–149], he has also established significant global connections, partnering with researchers from the USA, UK, and Denmark[150–156]. It is evident from their position at the forefront of the collaboration network, alongside Yang F and Yang Z, who occupy the second and third positions. The visualization effectively illustrates the dynamic and interconnected nature of ORC research collaborations, with Zhang H, Yang F, and Yang Z playing a pivotal role in shaping the research landscape.

4.9 Conceptual Structure

The conceptual structure of a field provides a framework for understanding the main themes, subthemes, and patterns that shape the area of research[107]. The conceptual structure of ORC research can be deconstructed by analyzing co-occurring words. It involves identifying essential themes and subfields and mapping them onto a bi-dimensional matrix through thematic analysis.

4.9.1 Thematic analysis

The thematic map in Fig. 17 illustrates the ORC literature landscape from 2013 to 2023, featuring keywords with a minimum occurrence frequency of 15. The 200 keywords within the dataset were analyzed using the Walktrap algorithm, suitable for network sizes[157]. The thematic map categorizes the themes into four quadrants based on their relevance and level of development: Motor theme (highly relevant and highly developed), basic theme (highly relevant but less developed), Emerging or declining theme (less relevant and less developed), and Niche theme (less relevant but highly developed).

The motor theme, comprising several highly relevant themes to further development of ORC, includes crucial aspects such as waste heat recovery, working fluid selection, optimization techniques, and zeotropic mixtures within ORC applications. Waste heat recovery is a cornerstone in sustainable energy practices, connected to 428 documents, aiming to harness and convert low-grade heat into helpful power[158]. The choice of working fluid is pivotal, influencing the ORC's efficiency and performance. Researchers explore a plethora of working fluids, evaluating their thermodynamic properties to enhance the overall efficiency of the cycle[159].

Optimization techniques are central in refining ORC systems, ensuring they operate at their maximum potential. It involves intricate analyses of parameters such as temperature, pressure, and mass flow rates to achieve optimal performance[160]. Zeotropic mixtures, characterized by varying compositions, offer the potential for improved cycle efficiency and performance compared to single-component working fluids[161,162].

The Basic theme encompasses thermal efficiency, heat recovery, and exergy analysis. The Emerging theme focuses on the scroll expander. The Niche theme gains prominence in the upper-left quadrant, highlighting themes such as exergy, energy, genetic algorithm, and efficiency. The themes in this cluster are still underrepresented in ORC research but have the potential for further development in future studies. Therefore, the themes within this cluster can be utilized as alternative research avenues in ORC to address knowledge gaps not covered in the Motor theme.

Integrating exergy analysis into engineering practices marks a modern approach to enhancing system performance by pinpointing and alleviating sources of exergy loss. The close relationship between energy and exergy positions them within the same cluster. Research on exergy demonstrates a broader scope than energy, correlating with only 49 documents. Exergy extends its influence across various domains, including energy storage, combined cycle, trigeneration, gas turbine, biogas, biomass, solid oxide fuel cell, concentrated solar power, thermoeconomic, and exergoeconomic.

Genetic algorithms emerge as the Niche theme, revolving around efficiency, thermal energy storage, exergoeconomic, solid oxide fuel cell, combined cycle, LNG, and biomass. These algorithms play a crucial role in parametric optimization[163–166], thermoeconomic evaluation[167–170], and fluid selection[171–174] within the ORC context.

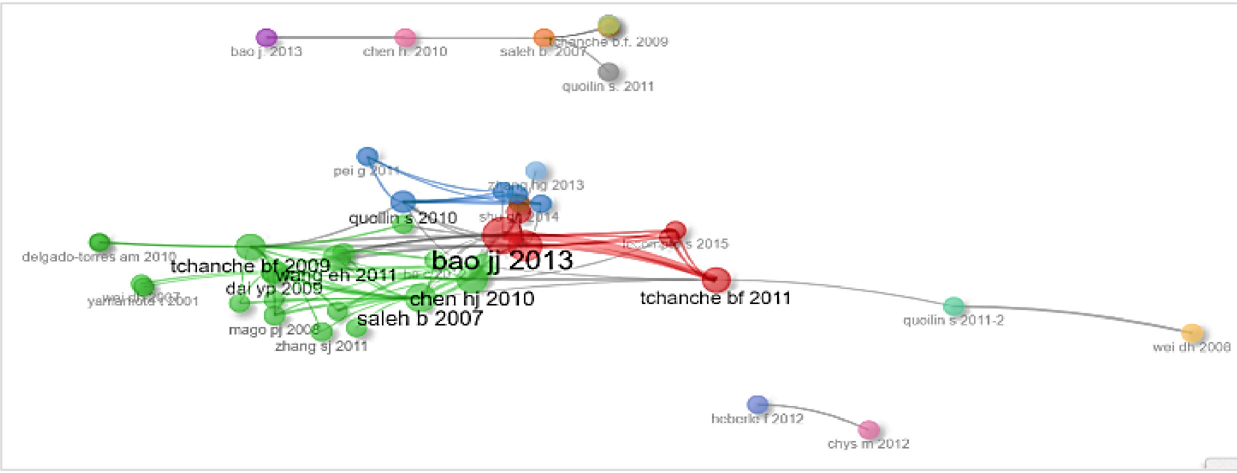

Fig. 14: co-citation network.

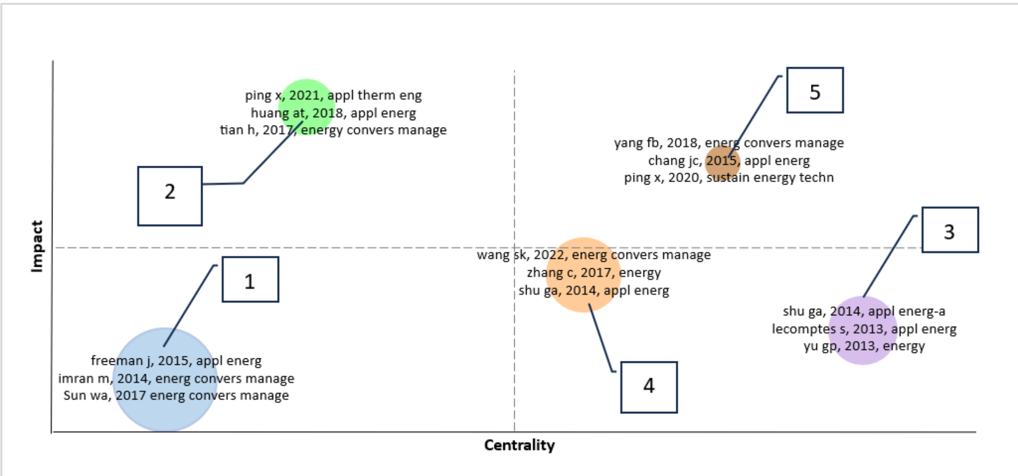

Fig. 15: Coupling analysis clusters.

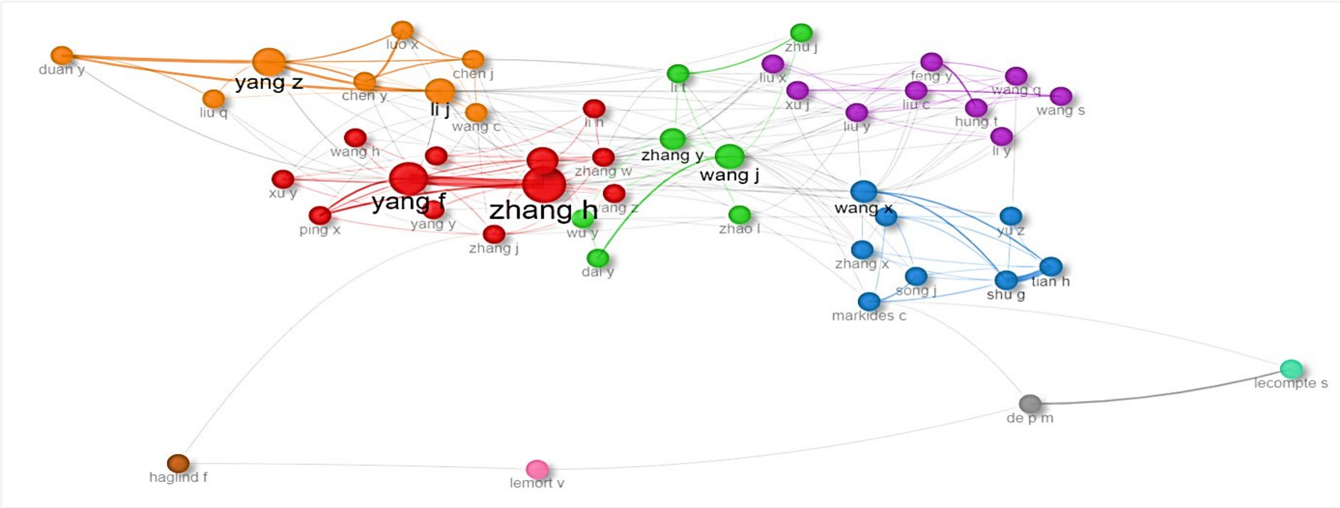

Fig. 16: collaboration network.

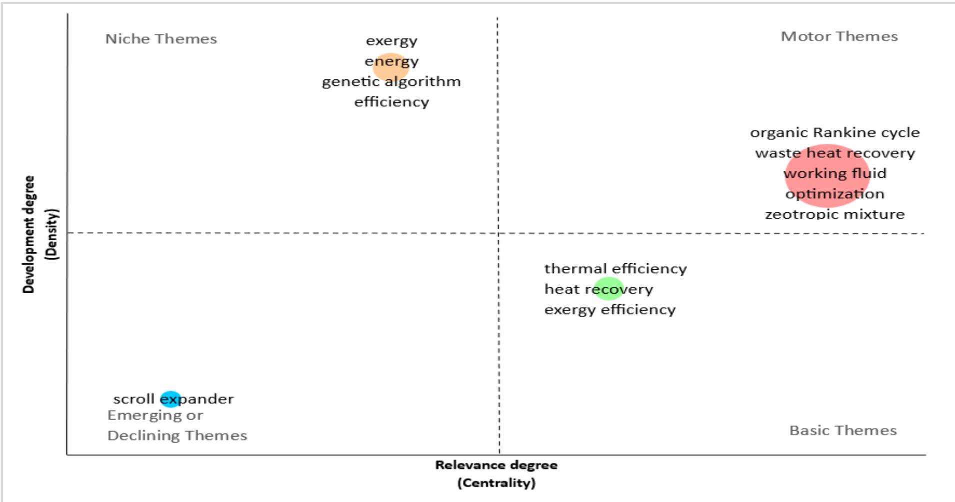

Fig. 17: Thematic map.

4.7.3 Research Trends

Fig. 18 illustrates the trend of ORC research topics based on the author's keywords, with a minimum word frequency of 10 and a yearly word count of 3. The figure shows that the trajectory of ORC research from 2013 to 2023 reveals key thematic trends indicative of the technology's evolution within the renewable energy landscape. The persistent emphasis on "Organic Rankine Cycle" as a prevalent keyword underscores its enduring significance, suggesting sustained interest in harnessing low-temperature heat sources efficiently.

Notable trends include the escalating focus on "Waste Heat Recovery" since 2016, reflecting a concerted effort to optimize ORC systems for industrial applications. The emergence of "Multi-Objective Optimization" in 2018 signifies a shift toward holistic optimization strategies, while recent keywords like "Machine Learning" and "Energy Storage" indicate a widening scope of ORC research into novel domains, aligning with contemporary technological advancements and environmental considerations.

This dynamic evolution underscores ORC's adaptability and continued relevance in advancing renewable energy solutions. The trend analysis highlights the technology's capacity to evolve and respond to emerging challenges and opportunities in the renewable energy sector.

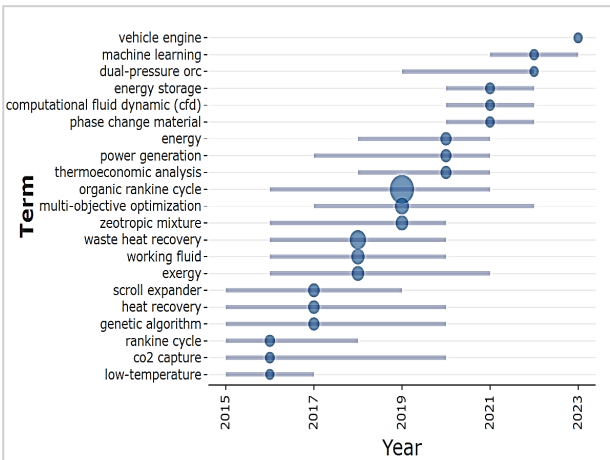

Fig. 18: Trend topics.

Table 6 presents a trend analysis of ORC cycle concepts derived from filtering documents using author keywords and document titles related to available ORC concepts[175]. Transcritical and supercritical ORCs maintain consistent attention, with 104 and 144 documents. The data consistently focuses on transcritical and supercritical ORCs, with 104 and 144 documents indicating sustained efforts to enhance performance under extreme conditions.

The trend also shows a growing interest in recuperative ORCs, with 26 publications emerging in 2017, highlighting a focus on heat exchanger integration. Regenerative ORCs, with 84 documents, demonstrate continued interest in preheating working fluids. Multi-stage ORCs, with eight documents, suggest an exploration of intricate configurations.

Reversible heat pumps and flash ORCs indicate interest in reversible applications and isentropic expansion. Trilateral ORCs, with 12 publications, represent a concentrated exploration period from 2016 to 2021. Partial evaporation ORCs, with two documents in 2023, suggest an emerging avenue.

Table 6. The trend of cycle concept.

Cycle Type	No. of Doc	Publication Time
Transcritical	104	2013-2023
Supercritical	144	2013-2023
Recuperative	26	2017-2023
Supercritical CO2	55	2013-2023
Regenerative	84	2013-2023
Multi-stage	8	2017-2023
Reversible heat pump	19	2015-2023
Flash	31	2014-2023
Trilateral	12	2016-2021
Partial evaporation	2	2023

4.10 Discussion

The current study provides a comprehensive analysis of the evolution of ORC research from 2013 to 2023, offering a broader perspective compared to previous studies. The analysis reveals that the publication output, authorship, and citation frequency in ORC research have experienced a substantial increase over the past decade, corroborating previous findings[21,31]. This escalating trend reflects the growing significance and complexity of this field.

Notably, our study reveals that the number of publications has increased from 2,120 articles by 3,443 authors to 2,462 documents by 3,753 authors, with an average citation rate rising from 17 to 23.3 per document. It indicates a growing academic interest in ORC and its increasing impact, surpassing the reported 17 citations per paper for the 2000-2016 period[31].

Geographically, our study confirms that China remains the dominant force in ORC research, followed by significant contributions from the United States and European countries. Iran has risen to prominence in the past decade, underscoring the increasing value of international collaboration and diverse perspectives in driving research innovation.[31].

The analysis of intellectual structure reveals two key findings: the fundamental elements that have driven the development of ORC research and the emerging research fields that are driving innovation in this field. The co-citation analysis identifies three clusters crucial to the development of ORC: optimizing working fluid selection, designing and modeling ORC components such as turbines and scroll expanders, and evaluating the performance of ORC working fluids. Furthermore, the bibliometric analysis reveals five new research clusters that have emerged to drive innovation in ORC, including thermoeconomic analysis, optimization, thermodynamic analysis, working fluid selection methods, and experimental testing of ORC performance. Our study reveals two novel findings not previously documented in the existing literature[21,31].

The results of the conceptual structure analysis indicate that the thematic focus of ORC research has undergone significant changes and has expanded to encompass a broader range of topics. The research focus is no longer limited to basic themes such as working fluid selection, cycle architecture, and optimization. Still, it has shifted to include emerging areas such as waste heat recovery, zeotropic mixture application, and genetic algorithm application. The research introduces new areas of investigation in ORC that have not been previously explored in the literature[31]. The current trend of ORC research is characterized by a growing diversity of research approaches and applications, focusing on improving ORC performance through innovative methods such as multi-objective optimization and machine learning. These advancements address pressing energy conservation challenges and facilitate the development of new energy sources[21,31].

Furthermore, the analysis of social structure using co-authorship relationships reveals a previously unknown global network of connections in ORC research, emphasizing the significance of international collaboration in advancing knowledge and innovation in the field [21,31]. A key figure in this network is Zhang H, who has collaborated with researchers across multiple countries. The visual representation of the network highlights the dynamic and interconnected nature of ORC research, with Zhang H, Yang F, and Yang Z serving as central hubs. It underscores the importance of international collaboration in driving progress in this field and underscores the potential for solid global partnerships to accelerate innovation and address energy challenges.

4.11 Future Research Directions in ORC Research

As the field of ORC technology continues to evolve, several emerging trends, technological advancements, and interdisciplinary collaborations hold the potential to shape its future. Based on the current literature and ongoing research efforts, we identify several critical areas that emerge from current literature and ongoing research efforts. First, advancing the development and evaluation of new working fluids, particularly zeotropic mixtures, and supercritical fluids, stands out for enhancing ORC efficiency and adaptability. Integrating ORC systems with renewable energy sources like solar and geothermal energy presents promising opportunities to optimize energy extraction and project economics. Cascade and hybrid ORC systems, such as those combining supercritical CO_2 cycles, offer the potential for improving energy conversion efficiency and reducing environmental impact through optimized configurations and heat exchanger designs. Comprehensive economic and environmental analyses are essential for assessing ORC's long-term viability, including its impact on carbon emissions and sustainability. Interdisciplinary collaborations, integrating materials and data science advancements, can drive innovation in ORC applications such as waste heat recovery and desalination. Continued focus on performance optimization through advanced techniques like genetic algorithms will refine ORC systems for maximum efficiency and minimal environmental footprint. Lastly, exploring emerging applications such as ORC coupled with battery storage and its use in off-grid settings expands the potential of ORC technology beyond traditional power generation, paving the way for sustainable energy solutions in diverse fields.

5. Conclusion

This study offers a detailed examination of the Organic Rankine Cycle (ORC) research landscape over the past decade. Through a quantitative bibliometric analysis of Scopus and Web of Science databases, we have achieved our objectives of analyzing publication development, investigating knowledge structures, examining research trends, and mapping future research directions in ORC technology.

The systematic search focused on the keyword "organic Rankine cycle" yielded a comprehensive dataset of 2,462 scholarly articles published between 2013 and 2023. The articles were authored by 3,753 researchers and exhibited a significant growth trend, with peak publication rates in 2017 and 2020. Notably, the annual publication rate was 24.61, with an average citation rate of 23.3 per year per document. This analysis highlights the enduring popularity of ORC research yet underscores the importance of considering factors that hinder research progress in this field for future studies.

Top authors, including Zhang H, Zhang Y, and Yang F, have significantly shaped the research discourse in ORC. Specifically, Zhang H stands out as the most influential author, as evidenced by their impressive H-index, G-index, and TC (2,349) metrics. A social network analysis also reveals that Zhang H has an extensive network of collaborations with researchers from both national and international institutions. Zhang H's research findings can serve as a primary reference for identifying knowledge gaps and trends in ORC. Moreover, collaborating with Zhang H can provide researchers with opportunities to ensure the quality of their research and stay abreast of the latest advancements in this field.

The paper written by Colonna P. in the Journal of Engineering for Gas Turbines and Power has achieved the highest global citation rate, with 302 citations and an average of 30.2 citations per year. This paper is a primary reference in ORC research, comprehensively understanding ORC technology's fundamental concepts and applications. A network analysis of the papers cited in the ORC field reveals that the core elements of ORC research development are clustered into three main areas: working fluids, turbine design, and organic fluids' performance. Researchers in ORC can leverage these three primary trends and the corresponding papers to inform their research interests and refine their focus.

China is a leading nation in ORC research, boasting the most prominent contributions and extensive collaborative network nationally and globally. Chinese research institutions and authors are renowned for their pioneering work in the field, driving advancements in ORC technology. Furthermore, a social structure analysis reveals that China is a crucial hub for knowledge development in ORC. Consequently, researchers from other countries, particularly those from developing countries, who are interested in conducting research in this field are advised to establish collaborations with Chinese institutions to leverage the global research trends and contribute to novel knowledge related to ORC.

In addition, "Energy" stands out as the most influential source in ORC research, boasting a substantial 13,500 citations and a remarkable H-index. This journal leads the pack in publishing the most articles on the topic, making it a valuable resource for researchers seeking to stay abreast of the latest developments and most impactful findings in ORC.

A keyword and co-occurrence analysis reveals that the keywords "organic Rankine cycle," "waste heat recovery," and "working fluid" are consistently the most frequently cited terms in ORC research. Complementary analyses, including co-citation analysis, bibliometric coupling, thematic mapping, and co-authorship network analysis, have comprehensively mapped ORC research's intellectual, social, and conceptual structure. The results reveal distinct clusters and collaborations that drive innovation and progress in the field. Key themes, including optimization, thermoeconomic analysis, and emerging areas like machine learning and energy storage, have emerged as focal points of research attention. Moreover, trend analysis indicates sustained attention to transcritical and supercritical ORCs, alongside growing interest in recuperative and regenerative ORCs, underscoring ORC's adaptability and relevance in advancing renewable energy solutions.

The identified trends and themes in ORC research have significant implications for the field's future. Research should focus on advanced materials and working fluids to enhance thermal stability and efficiency. Exploring hybrid systems that combine ORC with renewable technologies like solar PV and wind can boost energy output and reliability. Optimizing the design and operation of transcritical and supercritical ORCs and developing recuperative and regenerative ORC systems for heat recovery and energy storage are critical priorities. Integrating machine learning and AI can enable real-time optimization and predictive maintenance. Comprehensive thermoeconomic analyses will offer valuable insights into ORC systems' economic and environmental impacts. Additionally, experimental validation of numerical simulations and modeling techniques is essential for accurate performance prediction and reliability.

Despite these promising trends, ORC research faces several limitations and challenges that must be addressed to realize its full potential. High initial costs and long payback periods can deter investment in ORC technology, while the design and optimization of ORC systems involve complex thermodynamic and material challenges. Additionally, the lack of standardized testing and performance metrics can hinder the comparability and scalability of different ORC systems. To overcome these challenges, researchers should conduct comprehensive cost-benefit analyses to demonstrate the long-term economic benefits of ORC systems, and policymakers should provide incentives and subsidies to offset initial investment costs. Research should also focus on advanced materials and working fluids that can withstand high pressures and temperatures, and international standards for ORC system performance should be developed and adopted.

In addressing future research directions for ORC technology, specific recommendations include enhancing computational fluid dynamics (CFD) simulations for precise system design, fostering collaborative partnerships among academia, industry, and government for accelerated technology implementation, and integrating interdisciplinary expertise to innovate new working fluids and optimize predictive maintenance using machine learning. International consortia should also be established to promote global knowledge exchange and standardization, which is crucial for advancing ORC technology on a broader scale and across various applications. These strategies aim to propel ORC innovation towards sustainable energy solutions effectively.

Nomenclature

ORC	organic Rankine cycle
WoS	web of science
WHR	waste heat recovery
LNG	liquefied natural gas
RC	recuperator ORC
RG	regenerative ORC
OFC	organic flash cycle ORC
TCC	trilateral cycle ORC
TCC	transcritical ORC
MP	multiple evaporation pressures ORC
TC	total citation
CHP	combined heat and power
CHP	combined heat and power plant
NP	number of publications
PY_start	publication year_start

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