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*Review Article*

# Bibliometric Analysis of Research Trends in Steam Boiler Efficiency Improvement

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**Abstract**

Steam boilers are widely used in power generation and industrial processes. Improving their efficiency is crucial for enhancing sustainability and reducing operating costs. This study conducts a comprehensive bibliometric analysis to map the evolving research landscape on steam boiler efficiency improvement from 2014 to 2023. A literature search in the Scopus database retrieved 3574 publications. This study employs bibliometric analysis using Bibliometrix R packages and VOSViewer software to examine research trends, focusing on publication growth, key journals, influential authors, and emerging themes in steam boiler efficiency improvement. The results indicate a significant increase in annual research output, reflecting sustained global efforts in the field. China leads in both the volume and impact of contributions. Key research themes include materials development, innovative designs, heat recovery, and sustainable solutions. Notable publications emphasize eco-friendly approaches such as solar and organic thermoelectrics. Prolific authors from China, the United States, and Europe have shaped the discourse through influential collaborations. Emerging trends highlight a growing focus on renewable energy integration, advanced thermal management, and computational methodologies. This study consolidates knowledge on enhancing steam boiler efficiency through both quantitative and qualitative analyses, showcasing remarkable progress driven by dedicated international efforts. These insights can inform future strategies and inspire innovation in optimizing this critical energy conversion process.

***Keywords:*** *Boiler; steam generator; efficiency; bibliometric analysis; literature review.*

## 1. Introduction

Energy utilization serves as a key indicator of progress. Population growth, urbanization, industrial expansion, and technological advancements have significantly increased global energy demand. However, this rapid rise has also contributed to environmental challenges, including pollution and climate change. Currently, fossil fuels generate 80% of the world's electricity, while renewable sources account for the remaining 20% [1], [2], [3]. Global electricity demand is rising steadily at an annual rate of approximately 6% [4], [5]. The widespread use of fossil fuels is a major contributor to $CO_2$ emissions [6], [7], [8]. Thermal power plants can be categorized into four main types: cogeneration systems, combined-cycle power plants, natural gas-fired power plants, and coal-fired power plants [7], [9], [10].

Steam boilers are essential components of thermal power plants, generating high-pressure superheated steam to drive turbines for electricity production. Enhancing boiler efficiency and performance is critical to improving the sustainability and competitiveness of coal-based power generation [11], [12], [13], [14]. This process requires the seamless integration of various components, including the furnace, superheater, evaporator, air preheater, and economizer, along with auxiliary systems such as pumps, fans, burners, and chimneys [15], [16], [17]. Given the depletion of fossil fuel resources and rising environmental concerns, there is a growing need for more efficient boiler operation [18], [19], [20], [21], [22], [23]. This demand has driven advancements in boiler design, emphasizing the identification and reduction of major thermodynamic losses. A comprehensive performance assessment of boiler systems is essential for pinpointing inefficiencies and prioritizing necessary modifications [14], [24], [25]. The components responsible for the highest thermodynamic losses offer the most potential for improvement. Despite numerous international environmental agreements, many boilers continue to operate with suboptimal control settings, resulting in efficiencies lower than manufacturer specifications [7], [26], [27].

The pursuit of efficient energy utilization is a cornerstone of modern industrial development and sustainability efforts. In this context, steam boilers, essential across various sectors, require continuous innovation to enhance performance and minimize energy waste [28], [29], [30], [31]. This bibliometric study provides a comprehensive analysis of the evolving landscape of steam boiler efficiency improvements, examining key research trends, groundbreaking advancements, and emerging directions in the field. As critical components of energy conversion and industrial processes, steam boilers play a vital role in energy-intensive sectors such as power generation, manufacturing, and heating systems. However, optimizing their efficiency remains an ongoing challenge, requiring a deep understanding of technological advancements, methodological approaches, and material innovations [32], [33], [34], [35], [36], [37].

This bibliometric study endeavors to map and analyze the extensive body of literature encompassing seminal works, research trajectories, and transformative insights elucidating the nuanced landscape of steam boiler efficiency enhancement. Spanning a wide array of disciplines, the investigation aims to distill trends, identify key contributors, and chart the progression of innovative strategies and technologies poised to redefine the efficiency paradigm in steam boiler operations. With energy conservation and sustainability at the forefront of global concerns, the impetus to elevate the efficiency of steam boilers is paramount. This research serves as a comprehensive compass, navigating through the vast corpus of scholarly endeavors, consolidating knowledge, and paving the way for a deeper comprehension of the evolving trends and future directions in steam boiler efficiency improvement [38], [39], [40], [41], [42], [43], [44] Bibliometrics has gained substantial importance within information science, particularly in monitoring information and managing knowledge. Recent studies have extensively explored bibliometric patterns across a range of research areas, including management, econometrics, health economics, marketing, statistics, ecological economics, entrepreneurship, production and operations management, data envelopment, gray systems, and innovation [45], [46], [47], [48], [49], [50], [51], [52]. This rising trend emphasizes the acknowledgment of bibliometrics as a valuable tool for understanding and assessing research trends spanning diverse fields. This analytical method provides insights into the development, patterns, collaborations, structure, and impact within specific knowledge domains. Researchers leverage specialized software like Bibliometrix, VOSviewer, and CiteSpace to perform bibliometric analyses, enabling the identification of information sources, acknowledging previous work, substantiating claims with evidence, and unveiling potential research avenues. This approach is integral to conducting comprehensive literature reviews, enabling researchers to analyze extensive bibliographic data and generate various graphs, maps, and indicators for thorough exploration and interpretation [53], [54], [55], [56], [57], [58], [59].

Secades et al. [60] reviewed waste heat recovery technologies for marine engine efficiency using bibliometric analysis and the PRISMA 2020 framework. From an initial 576 studies (Scopus & Web of Science), they refined their selection to 35 key papers. The Organic Rankine Cycle emerged as the leading method, with potential for cold energy recovery in LNG vessels. Thermoelectric generators were identified as a promising but underexplored area, highlighting a gap in research on low-grade waste heat recovery. Yu et al. [61] analyzed $SeCO_2$ cycle research (2000–2019) using Scopus and BibExcel, covering 724 publications, 1,378 authors, and 543 institutions from 55 countries. With an average of 13.39 citations per paper, the US led research, followed by China and South Korea. Their study categorized publications into applications, cycle configurations, $CO_2$-based mixtures, system components, and experiments, providing insights for advancing $SeCO_2$ power system commercialization.

Zahedi et al. [62] analyzed $CO_2$ capture in combined cycle power plants using bibliometric analysis and data mining. Using VOSViewer, they mapped key terms, tracked publication trends, and examined CPC and IPC clusters. Their study highlighted energetic dark greenhouses as a promising $CO_2$ capture technology and proposed policy solutions for market failures. They concluded that coupling NGCC power plants with energetic dark greenhouses offers a highly efficient CCS solution with lower regeneration energy needs. Similarly, Omoregbe et al. [63] examined carbon capture's role in $CO_2$ reduction (1998–2018), noting a surge in research post-2008 due to climate policies. The US, UK, and China led the field, with post-combustion capture dominating (80.9%), while oxy-fuel combustion had the lowest share (3.4%).

Malekli et al. [64] explored $CO_2$ capture in combined cycle power plants using bibliometric analysis and data mining. Using VOSViewer, they clustered topics, tracked publication trends, and analyzed Cooperative (CPC) and International (IPC) Patent Classifications. The study aimed to enhance power plant efficiency by addressing energy gaps through Post-Combustion $CO_2$ Capture (PCC). Key recommendations included optimizing PCC via exergy and pinch analysis and integrating the Organic Rankine Cycle (ORC) to improve net power output. They also identified market failures, suggesting policy solutions. Gap analysis highlighted opportunities for renewable integration and improved energy efficiency. Ultimately, PCC with tertiary amine absorbents was identified as the most efficient CCS technology for NGCC plants due to lower regeneration energy demands. Similarly, Belmonte [65] conducted a bibliometric analysis on Integrated Solar Combined Cycles (ISCC) from 1990 to 2020 using Web of Science data. The study covered 1,277 publications, 3,157 authors, 1,102 institutions, and 78 countries. Energy Conversion and Management led in publications (158 articles), while Solar Energy had the highest citations (4,438). China was the most productive country (241 publications), with major contributors including the Chinese Academy of Sciences (52 articles) and I. Dincer (24 articles). Keyword analysis provided insights into future ISCC developments and its role in global solar energy research.

Karakurt et al. [66] conducted a bibliometric analysis of steam turbine research (2000–2020) using Scopus, examining 11,751 publications from 652 authors, 500+ institutions, and 101 countries. They analyzed publication types, core domains, influential journals, citation trends, authorship patterns, affiliations, and keyword frequencies. Energy was the most prolific journal, Ibrahim Dincer the leading author, and Singapore ranked highest by Paper Impact Parameter (PIP). Turbomachinery emerged as the dominant research field, with engineering disciplines showing the highest publication-to-citation ratio. Similarly, Permana et al. [67] explored solar applications in Organic Rankine Cycle (ORC) research (2010–2020) through Scopus-indexed bibliometric analysis, covering 1,249 documents, 1,217 authors, 140 institutions, and 56 countries. Major contributors included China, the USA, and Europe. The study identified "Organic Rankine Cycle" and "solar energy" as key research themes, with emerging trends in exergoeconomic analysis, polygeneration, and phase change materials for thermal energy storage.

In the broad field of steam boiler efficiency improvement, there remains a noticeable gap in up-to-date, comprehensive bibliometric analyses. Existing studies often fail to provide a holistic exploration of the entire knowledge landscape, overlooking interconnected research themes and emerging trends. A rigorous bibliometric study can bridge this gap by quantifying the literature, mapping research clusters, and identifying influential works, offering a nuanced perspective on the field's current state. Moreover, limited attention has been given to collaborative networks and authorship patterns. Understanding these collaborations is essential for fostering interdisciplinary efforts and advancing research in this domain. This underscores the need for a detailed examination of authorship networks within a comprehensive bibliometric framework. Additionally, the temporal evolution of research trends in this field remains underexplored. Tracking the development of technologies and scientific contributions over time can reveal innovation patterns and historical progress, enhancing our understanding of this dynamic area. A global perspective on steam boiler efficiency research is also lacking. Analyzing geographical distributions and regional factors influencing research priorities will provide valuable insights into how different parts of the world approach efficiency improvements. Finally, there is a critical gap in identifying and systematically analyzing emerging technologies and methodologies in this field. Addressing this deficiency is crucial for aligning research advancements with industrial needs and sustainability objectives. In summary, these gaps highlight the urgent need for a comprehensive bibliometric analysis of steam boiler efficiency research. Addressing them will not only provide valuable insights but also guide future research directions, enhance collaboration, and drive innovation in this critical area.

This study presents a comprehensive bibliometric analysis of Research Trends in Steam Boiler Efficiency Improvement (RT-SBEI), identifying key trends, influential contributors, and emerging research directions. By critically evaluating publication patterns and methodological approaches, we aim to provide a clear, succinct, and insightful overview that advances the understanding of steam boiler efficiency enhancemen the research delves into multiple dimensions regarding the enhancement of steam boiler efficiency. Firstly, it investigates the primary research domains and prevailing trends centered on augmenting steam boiler efficacy. Additionally, it scrutinizes the influential figures—both authors and institutions—actively propelling advancements in this realm. Moreover, the study aims to identify and assess the most cited and impactful publications within the sphere of steam boiler efficiency enhancement. Furthermore, it examines the evolutionary trajectory of research collaborations among authors and institutions in this specific field. Lastly, the inquiry explores the viability and promise of emerging technologies or methodologies poised to elevate steam boiler efficiency, offering potential avenues for further advancement.

## 2. Methodology

In detailing the methodology for conducting a literature review and bibliometric analysis, the Scopus database was selected as the primary resource. Its comprehensive document collection surpassed other databases like the Web of Science [68]. However, databases such as ResearchGate and Google Scholar were omitted from data collection due to their lower reliability in producing bibliometric outcomes.

The decision to utilize Scopus as the sole database for this study was driven by its extensive coverage of peer-reviewed literature in engineering and energy disciplines, which are central to research on steam boiler efficiency improvement. Scopus provides a reliable and comprehensive platform for bibliometric analysis due to its broad indexing of high-impact journals and citation records. Nevertheless, we acknowledge that this choice may limit the study's scope, as other databases like Web of Science could include additional relevant publications not captured in Scopus. To ensure the inclusion of only high-quality and relevant publications, this study applied strict exclusion criteria during the data collection process. The analysis was limited to peer-reviewed journal articles and reviews published in English, excluding conference papers, book chapters, and grey literature. This approach was adopted to prioritize rigorously evaluated research, which is widely regarded as the benchmark for academic excellence. By focusing on these sources, we aimed to enhance the reliability and applicability of the findings within the context of steam boiler efficiency improvement.

The exploration covered research conducted between 2014 and 2023, encompassing a substantial timeframe in the field. To initiate the process, a literature search was performed using a tailored query: ( ( "energy efficiency" OR "efficiency enhancement" OR "thermal efficiency" OR "energy optimization" OR "combustion optimization" OR "Combustion efficiency" OR "Fuel efficiency" OR "thermal performance" OR "efficiency improvement" OR "energy saving" OR "energy conservation" OR "performance improvement" OR "efficiency upgrade" ) AND ( "steam boiler" OR "steam system" OR "boiler system" OR "Heat generator" OR "Steam generation" OR "Steam power" OR "Boiler unit" OR "Power boiler" OR "Boiler equipment" OR "Boiler plant" OR "Steam production" OR "steam generator" OR "industrial boiler" OR "heat recovery system" OR "heat recovery boiler" OR "waste heat recovery" ) ).

The keywords employed in this bibliometric analysis were meticulously selected to reflect the scope of research on steam boiler efficiency improvement. Following a preliminary review of existing literature and discussions with experts in mechanical engineering and energy systems, we identified key terms such as 'energy efficiency,' 'thermal performance,' and 'steam boiler,' alongside related concepts like 'waste heat recovery' and 'combustion optimization.' These terms were combined using Boolean operators (e.g., AND, OR) to construct a tailored search query, executed within Scopus's title, abstract, and keyword fields. This filtering method excluded irrelevant topics, ensuring that the 3,574 retrieved documents accurately represent the research domain under investigation. The selection of keywords was based on an extensive preliminary review of the literature in steam boiler efficiency. Alternative keywords and their combinations were tested, and the final query was refined to maximize both precision and recall. For example, initial tests included terms related to waste heat recovery and thermoelectric applications, but these were further filtered to ensure direct relevance to steam boiler performance. This rigorous keyword selection process helped minimize the inclusion of unrelated studies and strengthened the reliability of our dataset. The specified keywords underwent a search within the document's title, abstract, and keyword sections, concluding on 25/12/2023. Our research was limited to publications in journals, specifically focusing on articles and reviews in English to ensure the inclusion of high-quality beer review articles. A total of 3,574 documents were identified and subsequently analyzed. This study spans the period from 2014 to 2023 to capture the most recent and transformative research in steam boiler efficiency improvement. This decade has been characterized by notable advancements, including the development of advanced materials, enhanced waste heat recovery technologies, and the integration of renewable energy sources into boiler systems. Additionally, this timeframe aligns with intensified global initiatives to improve industrial sustainability and mitigate carbon emissions, providing a pertinent context for analyzing research trends and innovations aimed at optimizing steam boiler performance. Figure 1 provides an outline of the methodological approach adopted for bibliometric analysis.

The gathered results were meticulously scrutinized to delineate trends and quantify works categorized by journal type, subject, countries, institutions, and authors. An exhaustive examination of keywords aimed to unveil prominent themes and emerging topics concerning Steam Boiler Efficiency Improvement, aiming to discern research trends and future prospects within the field. Additionally, to visually represent the interconnections among authors, countries, institutions, and keywords, the obtained results were graphically depicted using the bibliometrix library and biblioshiny application [69]. These resources, available as open-source software, were invaluable in extracting meaningful insights from the bibliometric database.

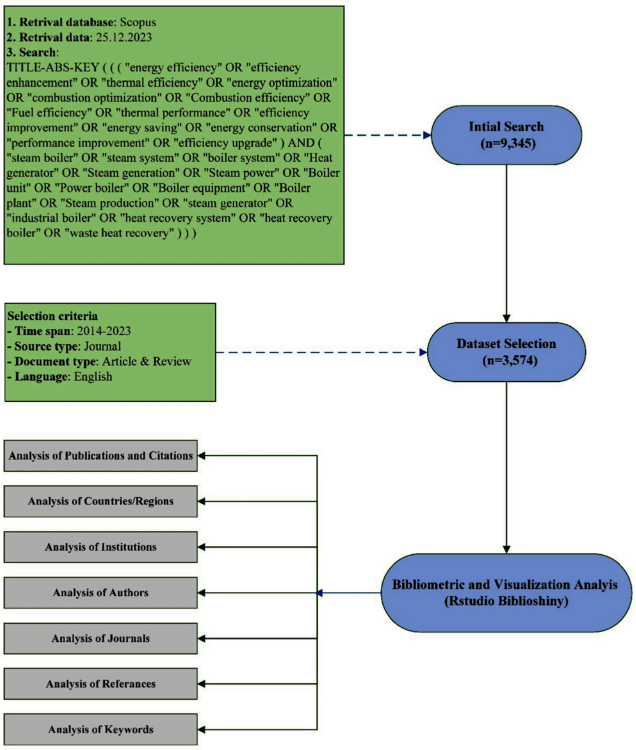



*Figure 1. A visual representation outlining the methodology adopted for bibliometric analysis.*

Bibliographic records and citation data were sourced from the Scopus API and analyzed using the Bibliometrix R package. Various dataset characteristics, including document types, publication years, source titles, authors, affiliations, citations, and collaborations, were systematically examined. Additionally, publication output, citation trends, and keyword dynamics were analyzed across different time frames. To identify key contributors and research networks, network visualization techniques were employed, highlighting influential countries, institutions, authors, sources, and collaborations. Centrality measures such as betweenness, closeness, and PageRank were computed to identify significant nodes within the research network. Furthermore, keyword co-occurrence analysis was conducted to uncover the intellectual structure and emerging trends within the field.

Visual representations, including treemaps and density visualizations, were utilized to identify highly represented topics. Where applicable, statistical tests such as Spearman's correlation were applied to ensure robust data interpretation. This bibliometric methodology provided both quantitative and qualitative insights into the evolving scholarly landscape of combined cycle power plant research on a global scale. It identified productive and influential researchers, assessed research impact, and highlighted core knowledge domains along with emerging topics requiring further exploration. The findings of this study offer valuable guidance for shaping future research directions and fostering collaborative opportunities within this critical area of energy technology. Despite its comprehensive approach, this study has certain limitations that should be acknowledged. First, the inclusion criteria were restricted to English-language articles, which may have led to the exclusion of relevant research published in other languages. Additionally, while Scopus provides a reliable and extensive database, variations in document selection and quantity may still arise. Furthermore, although the chosen keywords were highly relevant to the study's scope, incorporating alternative keywords could have potentially uncovered additional relevant documents. Recognizing these limitations is essential for contextualizing the study's findings and their broader implications.

## 3. Results and Discussion

### 3.1. Effect of Main Information

As shown in Table 1, the comprehensive bibliometric analysis of RT-SBEI covers a substantial period from 2014 to 2023, encompassing 602 sources and 3,539 documents, with a notable annual growth rate of 10.85%. Despite their relatively young average age of 3.6 years, these documents exert significant influence, achieving an impressive average of 25.97 citations per document, even in the absence of internal references.

*Table 1. General main information about the data regarding this study.*

| Description | Results |
|---|---|
| Timespan | 2014:2023 |
| Sources (Journals, Books, etc) | 602 |
| Documents | 3539 |
| Annual Growth Rate % | 10.85 |
| Document Average Age | 3.6 |
| Average citations per doc | 25.97 |
| Keywords Plus (ID) | 14285 |
| Author's Keywords (DE) | 8044 |
| Authors | 8079 |
| Authors of single-authored docs | 108 |
| Single-authored docs | 125 |
| Co-Authors per Doc | 4.39 |
| International co-authorships % | 22.83 |
| article | 3341 |
| article article | 32 |
| article review | 3 |
| review | 163 |

The depth of research in this field is evident from the extensive keyword usage, featuring 14,285 Keywords Plus and 8,044 Author's Keywords, highlighting the multidimensional nature of exploration within this domain. The collaborative aspect of this research is also pronounced, involving 8,079 authors, of whom 108 produced single-authored documents. Collaboration is prevalent, as reflected in an average of 4.39 co-authors per document and an international co-authorship rate of 22.83%. The dataset primarily consists of research articles (3,341), supplemented by article reviews (3), regular reviews (163), and a few other document types. This composition underscores the dominance of original research articles and the collaborative efforts driving advancements in steam boiler efficiency.

An analysis of the Annual Scientific Production trends within RT-SBEI, as illustrated in Figure 2, reveals a compelling progression from 2014 to 2023. The data exhibits a consistent upward trajectory in scholarly output, starting with 205 articles in 2014 and steadily increasing each year, reaching 518 articles in 2023. This growth underscores a significant rise in research interest and activity in this field. Notably, between 2017 and 2023, the pace of production accelerated markedly, reflecting an intensified focus on advancing knowledge in steam boiler efficiency. This steady annual increase highlights the sustained commitment of researchers and the broader scientific community to exploring and innovating strategies for improving steam boiler efficiency over the specified period. While the average annual growth rate of 10.85% in steam boiler efficiency research is substantial, it is important to contextualize this figure by comparing it with growth rates observed in other technological fields. Such comparisons indicate that the field of steam boiler efficiency is not only keeping pace with the overall expansion in scientific productivity but, in some respects, surpasses average trends, thereby underlining its emerging importance in energy sustainability research.

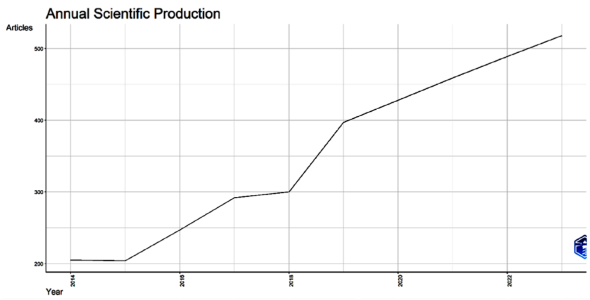


*Figure 2. Number of published articles over the investigation period.*

### 3.2 Sources Data

A bibliometric study on RT-SBEI, based on a Scopus search, identified 10 relevant publications between 2013 and 2023, as shown in Figure 3. The analysis of subject areas across these publications highlights a predominant focus on Energy and Engineering, with 2,309 and 2,107 papers, respectively. Environmental Science follows closely with 1,186 papers, while Chemical Engineering and Mathematics make significant contributions, with 564 and 547 papers, respectively. Other disciplines also play notable roles, including Materials Science, Physics and Astronomy, and Chemistry, each contributing over 200 papers. Beyond traditional STEM fields, Business, Management, and Accounting, as well as Computer Science, demonstrate engagement, each with over 100 papers. Additionally, Social Sciences, Agricultural and Biological Sciences, and Earth and Planetary Sciences contribute to a lesser extent, alongside interdisciplinary areas such as Biochemistry, Genetics, and Molecular Biology, Economics, and Medicine.

This comprehensive analysis underscores the multidisciplinary nature of research aimed at improving steam boiler efficiency, spanning both scientific and managerial domains.

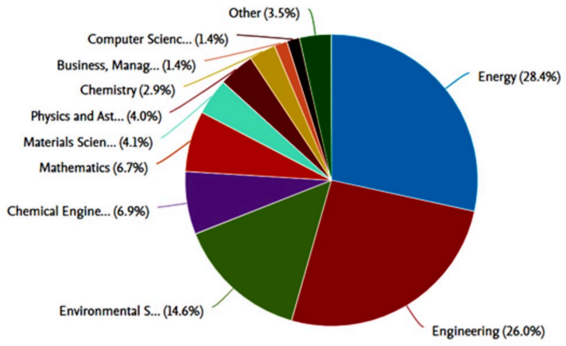


*Figure 3. Sharing articles by subject area.*

An examination of the local impact of sources contributing to the bibliometric landscape of RT-SBEI reveals several key insights. As shown in Table 2, *Energy* emerges as the leading source, with a high h-index of 61, reflecting substantial citation impact and broad influence within the field. It is closely followed by *Applied Energy* and *Energy Conversion and Management*, which also demonstrate strong citation impact, with h-indices of 58 and 56, respectively. These sources consistently perform well across various metrics, including the g-index and m-index, underscoring their sustained influence. Additionally, *Applied Thermal Engineering*, *Journal of Cleaner Production*, and *Renewable and Sustainable Energy Reviews* exhibit moderate to strong impact, each making significant contributions to the literature with distinct citation patterns. Meanwhile, *Energies*, *Renewable Energy*, *Energy and Buildings*, and the *International Journal of Hydrogen Energy* also play a role, albeit with relatively lower impact compared to the leading sources, highlighting their specialized niches within the broader research landscape on steam boiler efficiency improvement.

These findings collectively emphasize the diverse yet influential contributions of various sources in shaping scholarly discourse within this field.

*Table 2. Top 10 sources (Journals) related to combine cycle power plants field.*

| Journal | h_index | m_index | TC |
|---|---|---|---|
| Energy | 61 | 6.1 | 15060 |
| Applied energy | 58 | 5.8 | 10727 |
| Energy conversion and management | 56 | 5.6 | 10497 |
| Applied thermal engineering | 47 | 4.7 | 6977 |
| Journal of cleaner production | 30 | 3 | 2640 |
| Renewable and sustainable energy reviews | 28 | 2.8 | 3316 |
| Energies | 25 | 2.5 | 1841 |
| Renewable energy | 24 | 2.4 | 1443 |
| Energy and buildings | 16 | 1.6 | 854 |
| International journal of hydrogen energy | 15 | 1.5 | 880 |

An analysis of publication trends over time reveals intriguing patterns in the scholarly output related to RT-SBEI. As shown in Figure 4, ENERGY has demonstrated steady growth, beginning with 35 publications in 2014 and reaching a peak of 484 publications in 2023. This consistent upward trend highlights its sustained significance and contribution to the field. Similarly, ENERGY CONVERSION AND MANAGEMENT, APPLIED THERMAL ENGINEERING, and APPLIED ENERGY exhibit substantial growth trajectories over the same period, albeit with varying publication volumes. ENERGIES also shows a notable increase, though at a slightly slower pace compared to the others. The collective upward trend across these key sources reflects a strong and growing commitment to advancing steam boiler efficiency enhancement, underscoring the expanding interest and research efforts in this domain.

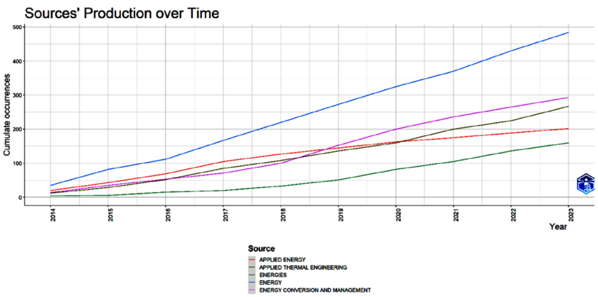



*Figure 4. Top 5 sources production over time.*

### 3.3 Country Data

The analysis of corresponding authors' countries provides valuable insights into the global landscape of RT-SBEI research. As illustrated in Figure 5, China emerges as the leading contributor, with 1,175 articles, highlighting its dominant presence in the field. Notably, China's strongest research collaboration is with India, reflecting a growing alliance between these two nations in this domain. Iran follows with 202 articles, demonstrating significant involvement, while the United Kingdom, the USA, South Korea, Turkey, Italy, and Poland also contribute notably, though with fewer publications. Among these countries, the United Kingdom stands out for its high collaboration ratio, emphasizing a strong inclination toward cooperative research efforts. This global participation underscores a collective and collaborative effort among nations to advance steam boiler efficiency, showcasing a shared commitment to innovation in this critical area.

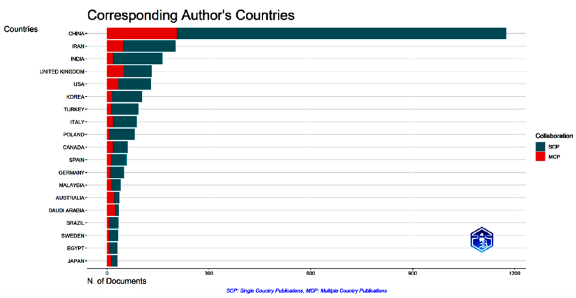



*Figure 5. Corresponding authors countries.*

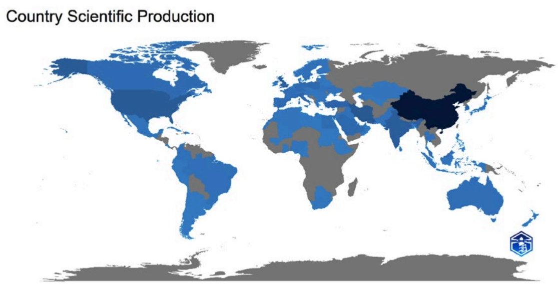



*Figure 6. Countries' scientific production.*

Figure 6 presents the scientific production of various countries within the RT-SBEI field. China leads with 2,700 articles, reinforcing its strong research engagement and leadership in this domain. Alongside China, Iran, the USA, India, and the UK exhibit substantial scientific output, further highlighting their significant contributions. Additionally, countries such as Turkey, South Korea, Italy, Poland, Saudi Arabia, and Malaysia also demonstrate noteworthy participation, albeit with lower publication frequencies. This broad and diverse global scientific production reflects a widespread international interest in enhancing steam boiler efficiency, emphasizing a collective commitment to advancing knowledge and technological innovations in this essential research area.

The analysis of Countries' Production over Time in the domain of RT-SBEI reveals compelling trends in scientific output across several nations. As reveals in Figure 7 China stands out significantly, displaying a remarkable escalation in scientific production from 103 articles in 2014 to a substantial 2700 articles in 2023, depicting a consistent and robust growth trajectory, emphasizing its pivotal role and enduring commitment to advancing research in this field. India, Iran, the United Kingdom, and the USA also exhibit substantial and escalating scientific output over the years, showcasing their sustained engagement and increasing contributions to the literature, albeit at varying growth rates. These nations collectively demonstrate a steadfast dedication to exploring steam boiler efficiency enhancement, showcasing a collective commitment toward pushing the boundaries of knowledge and innovation in this critical area of study.

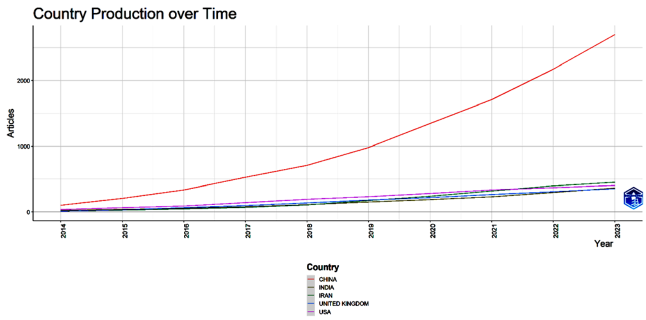



*Figure 7. Top 5 country production over time.*

The collaborative landscape of countries in steam boiler efficiency improvement is vividly illustrated through a comprehensive network. The data reveal intricate connections among nations actively engaged in this research domain. As shown in Figure 8 and Figure 9, China stands out as a central hub, fostering extensive collaborations worldwide, particularly with the United States and the United Kingdom. India also demonstrates significant involvement, forming strong research ties with China, Malaysia, and Saudi Arabia. The United Arab Emirates emerges as another key player, notably collaborating with Egypt and Malaysia, highlighting its active engagement in this field. Additionally, countries such as Canada, Germany, and Saudi Arabia exhibit diverse partnerships, reinforcing the global nature of research efforts in enhancing steam boiler efficiency. This intricate web of connections underscores the international scope of collaboration in this specialized domain, reflecting a collective commitment to advancing steam boiler efficiency across borders.

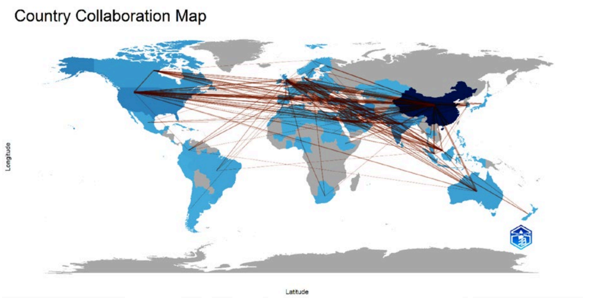



*Figure 8. Countries' collaboration world map.*

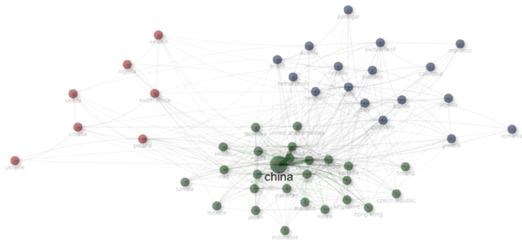
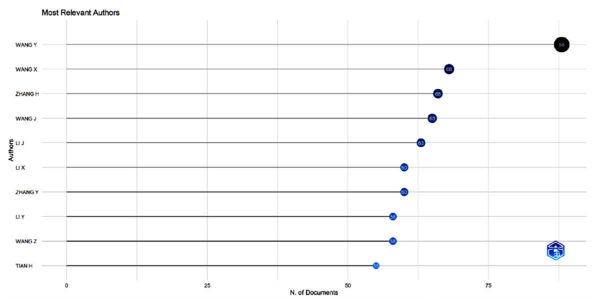


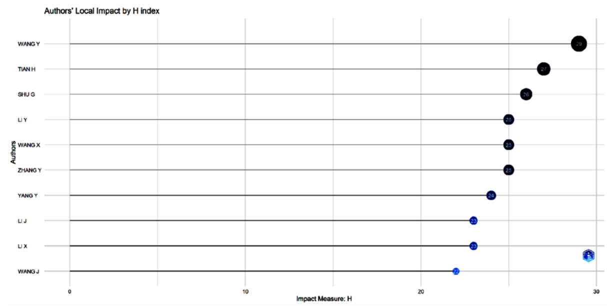

*Figure 9. Countries' collaboration network.*

### 3.4 Most Relevant Authors

In analyzing the most relevant authors contributing to the bibliometric landscape of RT-SBEI, several prolific researchers emerge as key contributors. As shown in Figure 10(A), Wang Y leads with 88 articles, holding a significant fractionalized share of 16.67%, highlighting his substantial impact in the field. Following closely, Wang X, Zhang H, and Wang J have published between 65 and 68 articles, demonstrating their noteworthy contributions to the literature. Li J, Li X, Zhang Y, Li Y, Wang Z, and Tian H also rank among the most productive and influential researchers, with their cumulative fractionalized contributions reinforcing their prominence in advancing steam boiler efficiency research. Collectively, these authors shape the scholarly landscape, playing a pivotal role in knowledge dissemination and innovation in this domain




*(A)*




*(B)*

*Figure 10. Top 10 most relevant authors: (A) Number of publications contributed, (B) Author contribution impact (h-index).*

Figure 10(B) presents the h-index values of several authors, reflecting their research impact and productivity in the field. Wang Y stands out with an impressive h-index of 29, followed closely by Tian H and Shu G, with h-indices of 27 and 26, respectively. Additionally, Li Y, Wang X, Zhang Y, and Yang Y demonstrate substantial influence, with h-indices ranging between 25 and 24. The contributions of Li J, Li X, and Wang J, with h-indices of 23 and 22, further highlight their significant involvement in advancing steam boiler efficiency research. Collectively, these authors represent a leading group in the field, with their impactful publications driving advancements and shaping the ongoing discourse on steam boiler efficiency enhancement.

Regarding author collaboration, as illustrated in Figure 11, the bibliometric analysis of the collaborative network in steam boiler efficiency research reveals distinct clusters and key contributors. In Cluster 1, Wang X emerges as a central figure, highlighting his significant influence and strong connections within this group. Closely following, Li X plays a pivotal role in facilitating information flow. Tian H, Shu G, and Shi L demonstrate moderate betweenness and closeness measures, indicating their active engagement in the collaboration network. In Cluster 2, Wang Y occupies a central position, signifying his influential role in knowledge dissemination. Additionally, Zhang H, Wang J, Li J, and Zhang Y play key roles, reinforcing their collaborative impact within this cluster. These findings reveal a diverse, yet interconnected network of authors dedicated to advancing steam boiler efficiency, underscoring the critical contributions of key researchers in knowledge exchange and collaboration across distinct clusters.

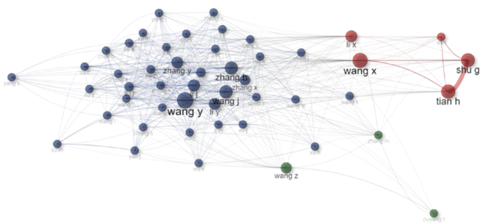



*Figure 11. Authors collaboration network.*

### 3.5 Most Relevant Affiliations

In analyzing the key affiliations shaping the bibliometric landscape of RT-SBEI, several institutions stand out as significant contributors. As depicted in Figure 12(A), Tsinghua University leads the field with 127 published articles, underscoring its pivotal role and prolific research output in this domain. Following closely, Xi'an Jiaotong University and North China Electric Power University have published 113 and 96 articles, respectively, reflecting their substantial engagement in advancing steam boiler efficiency enhancement research. Additionally, Tianjin University, Guangxi University, and Islamic Azad University make notable contributions, further reinforcing their impact on the scholarly discourse in this field. Other prominent institutions, including Zhejiang University, Shanghai Jiao Tong University, the University of Science and Technology of China, and the University of Tehran, collectively drive research advancements in steam boiler efficiency. Figure 12(B) illustrates the evolving research output of the top five affiliations over time, revealing dynamic growth trends. Notably, North China Electric Power University demonstrates consistent and impressive growth, increasing its publication count from just five articles in 2014 to 96 in 2023—an indication of its sustained commitment to this research area. Similarly, Tianjin University and Tsinghua University exhibit steady and significant expansion, with escalating publication trends that highlight their long-term dedication to steam boiler efficiency enhancement. Xi'an Jiaotong University also shows a remarkable upward trajectory, with its research output rising from three articles in 2014 to 113 in 2023, underscoring its substantial contribution to the field. Meanwhile, Guangxi University, despite a modest starting point, has demonstrated significant progress, culminating in 62 articles by 2023, an indication of its emerging role in steam boiler efficiency research. These trends collectively highlight the increasing and diverse institutional engagement in this field, reflecting a growing global commitment to advancing steam boiler efficiency improvements over time.

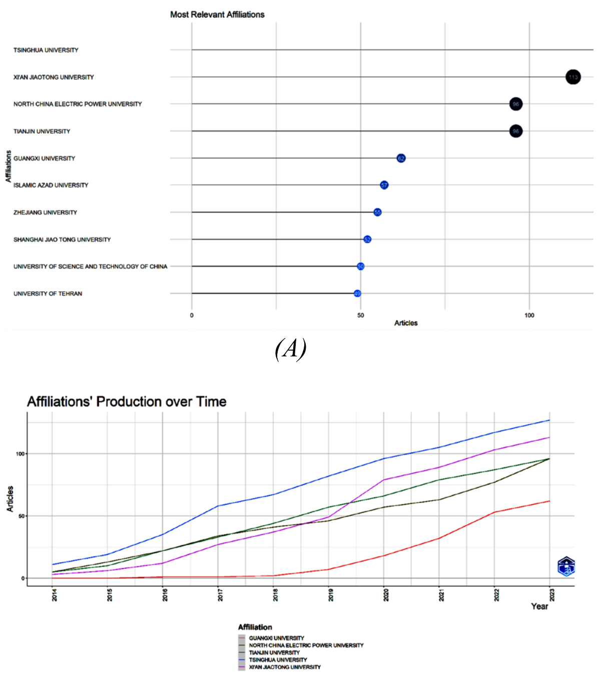



*Figure 12. Topmost relevant affiliations: (A) Number of publications, (B) Research output over time.*

### 3.6 Articles and Sources of Data

Table 3 presents the top 10 most-cited publications on steam boiler efficiency improvement from 2014 to 2023. These studies represent significant contributions to the field, highlighting emerging trends and key areas of research focus. Notably, many of these publications emphasize sustainable energy solutions, such as *"Solar Steam Generation by Heat Localization"* and *"Organic Thermoelectric Materials: Emerging Green Energy Materials Converting Heat to Electricity Directly and Efficiently."* These works reflect a growing shift toward eco-friendly approaches in enhancing steam boiler efficiency, aligning with broader research trends. The prominence of these studies is further reinforced by their publication in high-impact journals, including *Nature Communications*, *Advanced Materials*, and *Energy & Environmental Science*. Their presence in such esteemed journals underscores the quality and significance of their contributions.

An analysis of yearly citation rates and normalized total citations reveals distinct trends. While some papers consistently maintain high citation rates, reflecting sustained relevance and interest, others exhibit fluctuations, suggesting periodic surges in attention. Additionally, the breadth of topics covered in these highly cited publications is remarkable. From advancements in materials science—such as thermal conductivity enhancement using phase change materials—to innovative applications like simultaneous steam production and electricity generation, these studies showcase the diverse and multifaceted strategies driving progress in steam boiler efficiency. While phase change materials (PCM) [70] and thermoelectric (TE) studies [71] are not boiler-specific, their inclusion reflects their relevance to waste heat recovery in thermal syste*ms, a key sub-theme in steam boiler research.* It should be noted that while the keyword 'waste heat recovery' effectively captures a wide range of studies, it also encompasses research areas not directly related to steam generation. The inclusion of references dealing with phase change materials and thermoelectric applications reflects the interdisciplinary nature of waste heat utilization. We acknowledge this as a limitation in our methodological approach, and future research may benefit from more targeted keyword refinement to isolate studies specifically focused on steam boiler efficiency.

The normalized total citations (TC) in Table 3 were calculated to adjust for citation variations over time, providing a fair comparison across publications from different years. This metric is derived by dividing a publication's total citations by the average citation rate of articles published in the same year. The TC per year column was computed by dividing the total citations by the number of years since publication, offering insight into annual citation impact. These calculations ensure a robust assessment of publication influence.

*Table 3. The 10 cited publication in the Steam Boiler Efficiency Improvement from 2014 to 2023.*

| Ref. | Paper title | TC | TC /Year |
|---|---|---|---|
| [72] | "Solar steam generation by heat localization" | 1516 | 151.60 |
| [71] | "Organic Thermoelectric Materials: Emerging Green Energy Materials Converting Heat to Electricity Directly and Effi ciently" | 763 | 76.30 |
| [73] | "Waste heat recovery technologies and applications" | 583 | 97.17 |
| [70] | "Review on thermal conductivity enhancement, thermal properties and applications of phase change materials in thermal energy storage" | 549 | 91.50 |
| [74] | 3D-Printed, All-in-One Evaporator for High-Efficiency Solar Steam Generation under 1 Sun Illumination | 520 | 74.29 |
| [75] | "Wood–Graphene Oxide Composite for Highly Efficient Solar Steam Generation and Desalination" | 485 | 69.29 |
| [76] | "A 3D Photothermal Structure toward Improved Energy Efficiency in Solar Steam Generation" | 465 | 77.50 |
| [77] | "Robust and Low-Cost Flame-Treated Wood for High-Performance Solar Steam Generation" | 443 | 63.29 |
| [78] | "Nature-inspired salt resistant bimodal porous solar evaporator for efficient and stable water desalination" | 431 | 86.20 |
| [79] | "Scalable and Highly Efficient Mesoporous Wood-Based Solar Steam Generation Device: Localized Heat, Rapid Water Transport" | 408 | 68.00 |
| [79] | "Scalable and Highly Efficient Mesoporous Wood-Based Solar Steam Generation Device: Localized Heat, Rapid Water Transport" | 408 | 68.00 |

Overall, the analysis of these top-cited publications offers valuable insights into the evolving research landscape surrounding steam boiler efficiency improvement. It unveils not only the influential works but also the overarching themes, technological advancements, and diverse methodologies driving progress in this critical domain of energy efficiency.

The analysis of Most Frequent Words and Co-occuramce network Figure 13, and Figure 14 in the domain of RT-SBEI underscores critical themes and focal areas within the scholarly discourse. "Waste heat recovery" emerges as the most prevalent term, emphasizing the paramount importance placed on harnessing and utilizing wasted thermal energy. Additionally, concepts like "organic Rankine cycle (ORC)" and "exergy" signify a substantial interest in advanced cycles and efficiency metrics, respectively, highlighting a drive towards innovative energy conversion methods and rigorous efficiency assessments. Terms such as "optimization," "economic analysis," and "multi-objective optimization" underscore a clear focus on enhancing system performance while considering economic viability, reflecting a balanced approach towards maximizing efficiency and minimizing costs. Furthermore, phrases like "solar energy," "solar steam generation," and "thermal energy storage" point towards an exploration of sustainable and renewable energy sources alongside efficient storage mechanisms, showcasing an inclination towards environmentally friendly solutions in steam boiler operations.


Figure 13. Most frequent words.

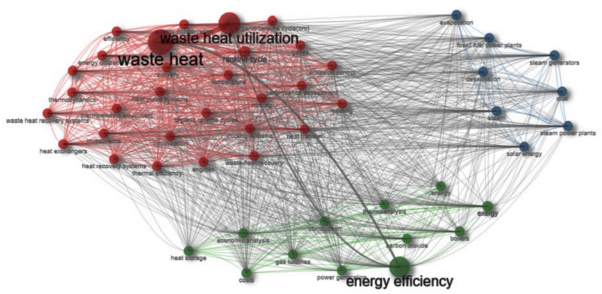



*Figure 14. Co-occuramce network on steam boiler efficiency improvements.*

In exploring RT-SBEI, a bibliometric study reveals a comprehensive thematic map (Figure 15) of key clusters and their centrality in the discourse. The thematic analysis comprises several clusters, including 'exergy,' 'waste heat recovery,' 'energy efficiency,' 'solar energy,' 'thermal energy storage,' and 'desalination,'. Among the prominent focal points, 'exergy' emerges with high centrality, Waste heat recovery remains pivotal, performance analysis. Furthermore, the discourse extends to energy efficiency, covering themes like energy recovery, energy storage, and diverse methodologies like genetic algorithms and techno-economic analyses. Solar energy and its applications, including solar steam generation and phase change materials, constitute a significant part of the research landscape. The data underlines a multifaceted discourse focused on enhancing steam boiler efficiency, spanning a spectrum from theoretical analyses to practical applications, with a growing emphasis on innovative, sustainable solutions like waste heat recovery and renewable energy integration.

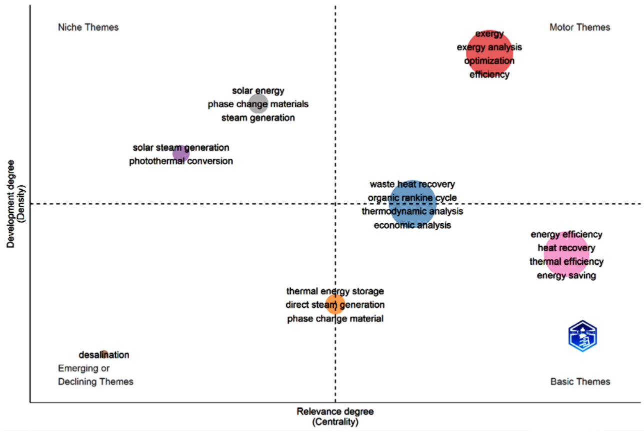



*Figure 15. Thematic map on steam boiler efficiency improvements.*

Examining the trends in Steam Boiler Efficiency Improvement topics (Figure 16) reveals a progression in research interests. In earlier years, focus was on "various operating conditions," "air pollution," and "bioethanol," marking concerns about operational variations, environmental impact, and alternative fuels. By the mid-2010s, emphasis grew around "ic engine," "rotary kiln," and "diesel engine," underscoring an interest in engine-related studies and combustion systems. The latter part of the decade saw attention shifting to "retrofit," "co2 emissions," and "combined cycle," highlighting retrofitting strategies and emission reduction in thermal systems. The 2017-2022 period witnessed a substantial rise in themes like "energy conservation," "waste heat recovery," and "organic Rankine cycle," showcasing a concentrated effort towards energy efficiency and waste heat utilization. Recent trends, from 2020 to 2023, emphasize "biomass gasification," "thermal management," "ammonia," and "emissions," signaling a move towards sustainable energy sources, advanced thermal control, and emissions reduction using computational methodologies.

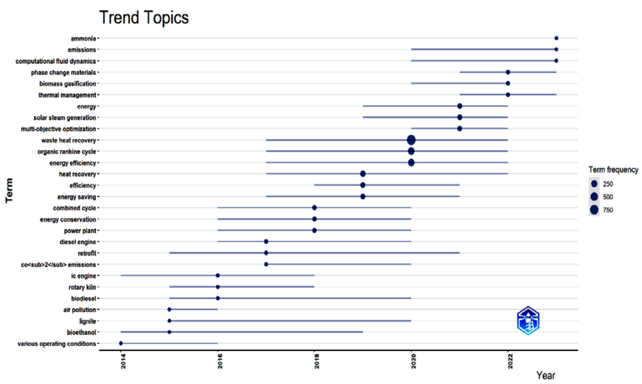



*Figure 16. Trend topics.*

## 4. Conclusion and Discussion

The bibliometric analysis provides valuable insights into the evolving landscape of steam boiler efficiency enhancement over the past decade. This comprehensive study highlights key publications, influential authors, leading institutions, and geographical contributions shaping this critical field. The steady increase in annual research output reflects the global research community's commitment to advancing innovations in steam boiler efficiency. Notably, China has emerged as a dominant contributor in both research volume and impact. However, significant contributions from countries such as the United States, the United Kingdom, and Iran have also enriched the broader discourse. Several key research themes are driving progress in this domain, including materials development, innovative designs, desalination and wastewater applications, and heat recovery technologies. In recent years, the focus has increasingly shifted toward exergy analysis, optimization methodologies, and the exploration of renewable and sustainable solutions, underscoring the industry's commitment to efficiency and environmental sustainability.

The statistical analysis reveals a pronounced dominance of research output from China, which can be attributed to several converging factors. First, China's substantial investment in research and development, particularly in renewable energy and advanced manufacturing technologies, has fostered an environment where innovative approaches to steam boiler efficiency are vigorously pursued. Second, supportive government policies and funding programs have incentivized both academic and industrial research, leading to a robust pipeline of high-impact publications. Additionally, China's strategic collaborations with international institutions have further enhanced its research capabilities, facilitating knowledge exchange and technological advancement. These collaborations are critical not only in amplifying research output but also in fostering a global research network that drives forward the frontiers of steam boiler efficiency. The implications of these trends suggest that a combination of policy support, financial investment, and international cooperation is key to achieving sustainable energy solutions in the coming years

Noteworthy publications highlight the growing emphasis on eco-friendly approaches, with advancements such as solar energy integration and organic thermoelectrics playing a key role in efficiency enhancement. Collaborations among prolific authors and esteemed institutions, particularly from China, the United States, and Europe, have significantly shaped the field through impactful partnerships. Emerging trends indicate an increasing focus on integrating computational tools, utilizing biomass, and implementing advanced thermal management strategies. Additionally, this analysis has identified key research avenues, including low-grade heat recovery, corrosion prevention, and the development of robust policy frameworks—areas that hold great potential for future exploration. The importance of international collaborations among leading contributors cannot be overstated, as they offer immense promise in accelerating progress by leveraging shared expertise and pooling resources effectively. Continued bibliometric monitoring remains a valuable tool for guiding future research strategies, fostering collaboration, and driving innovative breakthroughs. In conclusion, this study underscores the remarkable progress made in advancing steam boiler efficiency. It serves as a testament to the collective efforts of the global research community in pushing the boundaries of knowledge within this critical field.

**Limitations:**

The scope of this study is constrained by the availability and inclusivity of data sources used for bibliometric analysis. The potential omission of relevant publications due to database coverage limitations or language biases may affect the comprehensiveness of the findings. Additionally, inherent publication biases could influence the results, potentially skewing conclusions toward specific research areas or disproportionately highlighting positive outcomes. The temporal constraints of the analysis may also limit the representation of the most recent developments, potentially obscuring emerging trends. Furthermore, the methodology used to identify influential publications and assess impact may introduce a degree of subjectivity, which could affect the.

**Future Research Opportunities:**

Expanding the analysis to include a broader range of databases and sources could provide a more comprehensive overview of the scholarly landscape in steam boiler efficiency improvement. Incorporating qualitative assessments alongside bibliometric analysis would offer deeper insights into the context and substance of publications, enriching the understanding of emerging themes. Longitudinal studies tracking developments over extended periods could provide a more robust perspective on evolving trends. Additionally, integrating insights from diverse fields and conducting comparative studies across regions or industries could enhance the holistic understanding of efficiency enhancement strategies. Addressing specific gaps, such as low-grade heat recovery and policy formulation, presents opportunities for targeted and impactful research. Pursuing these research avenues would significantly contribute to both theoretical knowledge and practical application of steam boiler efficiency enhancement strategies.

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