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How Does the Digitalization Strategy Affect Bank Efficiency in Industry 4.0? A Bibliometric Analysis

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Abstract: This study conducts a detailed bibliometric analysis of the concept of bank efficiency, investigating its evolution in the scientific literature between 2000 and 2024 in the context of the digital transformation specific to the Industry 4.0 era. Using recognized databases, such as Web of Science and Scopus, the research explores the main trends and themes in the field, as well as the impact of emerging technologies on bank efficiency. Eight major thematic clusters are identified, including "risk", "'performance", "efficiency", "competition", "corporate governance" and "banking", highlighting key dimensions of recent research. The co-citation analysis highlighted central authors like Berger, Sufian, and Casu, along with distinct thematic and regional clusters, underscoring the diversity of research directions in banking efficiency. The co-citation analysis shows the influence of leading institutions and authors, including "University Putra Malaysia", "World Bank", and "NBER, United States", which have contributed significantly to the development of the literature. The results indicate that bank efficiency research is dynamic, multifunctional, and ever-expanding, providing an important foundation for future studies that will explore the challenges and opportunities for banks in the era of digitalization and sustainable development.

Keywords: banking efficiency; bibliometric analysis; Industry 4.0; Web of Science; Scopus

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1. Introduction

Banks are vital elements in the contemporary financial system, and their efficiency is of great importance for advancing economic development [1]. The importance of the banking sector derives from its central role as the main channel for saving and credit allocation in an economy [2,3]. Thus, banks perform a vital financial intermediation function, transforming deposits into productive investments [4].

In developing countries, where financial markets may be limited or absent, digitalization strategies within the banking sector play an important role in bridging gaps between savers and borrowers, ensuring an efficient and secure flow of funds [5]. According to Levine [4], the efficiency of financial intermediation, bolstered by digital advancements, significantly influences economic growth, with digitalized systems helping to prevent bank insolvencies and mitigate systemic crises. Moreover, banks are increasingly using digital tools to convert individual savings into productive investments within corporate and industrial sectors, which supports economic expansion. Digital transformation enables financial institutions to optimize their efficiency and productivity, adding substantial value to the overall economy. As Pruteanu-Podpiera et al. [6] note, strong, technologically advanced, and profitable banks are better equipped to meet stakeholder expectations and reduce the likelihood of failure. Therefore, assessing digitalization's impact on bank efficiency and identifying factors that influence performance are essential [7]. Banking efficiency, in this context, represents the capability to optimally utilize digital resources to maximize output with minimal cost [8–10].

Diallo [11] states that efficiency strengthens banks' resilience to shocks and has a positive and significant impact on economic growth, as banking efficiency alleviates credit constraints and supports finance-dependent industries during crises. Waheed and Younus [12] provide quantitative evidence that financial sector development and efficiency are important for stimulating long-term economic growth. An efficient banking system promotes economic progress and mitigates inefficiencies, with efficiency assessments helping managers identify areas for improvement essential to maintaining long-term competitiveness and profitability [13–15].

Digital transformation has triggered a paradigm shift in the banking industry, altering traditional banking operations and reshaping how financial institutions engage with their clients [16]. This technological evolution has not only streamlined internal processes but has also revolutionized customer interaction through innovative digital channels [17,18]. Furthermore, rapid advancements in information technology, data analytics, high-layer datasets [19], and artificial intelligence have fostered a digital ecosystem that surpasses geographical and temporal boundaries [20]. Consequently, as banks increasingly adopt digital platforms, the scope and scale of their operations have expanded substantially, enabling them to deliver a broad array of services, from mobile banking and digital wallets to virtual advisory services [21]. This positions the banking sector at a pivotal juncture, where the integration of digital tools is essential for enhancing operational efficiency and establishing institutions at the forefront of industry transformation [18,22].

The incorporation of digital technologies, including Industry 4.0, into banking has ushered in a new era of operational efficiency, redefining how financial tasks are executed, monitored, and optimized [23,24]. The automation and digitalization of routine tasks have minimized manual errors and accelerated transaction processing, resulting in significant time and cost savings. Additionally, digital platforms enable banks to collect, process, and analyze large volumes of data, providing insights that support informed decision-making in resource allocation, risk management, and service enhancement [16,25,26]. This shift towards digitalization has thus not only improved the efficiency of individual operational components but has also synergized various facets of banking operations, thereby amplifying the overall operational efficiency of the sector [27,28].

Digital transformation in the banking sector not only enhances operational efficiency but also supports sustainable development through a well-defined system of property rights that provides strong legal protection to investors, thereby encouraging their involvement in financial projects [16,29,30]. Furthermore, the integration of finance with digital technology gives rise to the concept of digital finance, which revolutionizes both production processes and lifestyles in contemporary society [31–33]. This digitalization emerges as a crucial catalyst for global economic growth, promoting the transition to smart, decentralized, and low-carbon energy systems, while also facilitating the adoption of renewable energy sources [34–37].

In the context of the rapidly evolving banking sector, efficiency in the use of financial resources has become a central topic of interest for both researchers and practitioners. Banking efficiency theory emphasizes the importance of optimizing processes and maximizing profitability, having a significant impact on a country's economic growth and financial stability. Within this theoretical framework, previous works have addressed different aspects of bank efficiency, but often in a fragmented manner, limited to specific contexts and without an integrated synthesis of the existing literature.

Thus, the aim of this paper is to conduct a detailed bibliometric analysis of efficiency in the banking sector, using data extracted from recognized databases such as Web of Science and Scopus. This analysis will provide a synthesis of research trends, identify the most influential authors and institutions, explore collaborative networks between researchers, and map the journals publishing the relevant work. Through these endeavors, we aim to contribute to a deeper understanding of the dynamics of bank efficiency and set directions for future research in this area, given the fundamental importance of efficiency for economic

development and financial sector stability. To this end, we propose a series of research questions that will be addressed throughout this paper:

RQ1: What is the trajectory of scholarly articles published so far on efficiency in the banking sector?

RQ2: What are the keywords used in the literature on efficiency in banking?

RQ3: Who are the most cited authors in the study of efficiency in banking?

RQ4: Who are the most prolific authors on this topic?

RQ5: Which are the main institutions that have investigated and published on this topic?

RQ6: Which journals publish the most articles on efficiency in banking?

RQ7: What are the most cited papers on efficiency in banking?

This paper is structured as follows: The introduction establishes the theoretical foundation, while the literature review identifies existing gaps in the research on banking efficiency. The Section 4 outlines the approach and tools employed in the bibliometric analysis. The subsequent analysis of the collected data presents the results and discusses the findings in detail. The paper then highlights our contributions to the research field and concludes with a summary of key insights, recommendations for policymakers, and an identification of research limitations along with suggestions for future research directions.

2. Literature Review

2.1. Banking Sector Efficiency

In reviewing the literature on the measurement of bank efficiency, studies have found varying results depending on the region and methodology used. Casu and Girardone [38] concluded that although cost efficiency initially increased in the EU-15 banking sector, EU integration did not have a significant impact on efficiency and inefficiency persisted. Brazil, Staub, Souza, and Tabak [39] found that state-owned banks had higher cost efficiency, while economic inefficiency was influenced by high macroeconomic volatility. Fiordelisi, Marques-Ibanez, and Molyneux [40] found that lower efficiency is associated with higher risk in banks, suggesting that more efficient banks become better capitalized.

Shafiee, Sangi, and Ghaderi [41] demonstrated that the dynamic Slacks-based measure (SBM) model is superior in evaluating the performance of Iranian banks, providing a more detailed picture of the relationship between profits and losses. Sharma and Dalip [42] showed that the Hicks–Moorsteen (HM) index provides a more accurate measure of the productivity of Indian banks compared to traditional DEA analysis. The study found low technical efficiency and showed that changes in scale efficiency had a dominant impact. They also found that productivity increased largely due to technical changes, with the results suggesting that traditional DEA analysis, based on the Malmquist index, underestimated efficiency and productivity levels compared to the HM index, which better takes into account external and environmental factors.

Aghimien et al. [43] provide insights on the influence of bank size and operational structures on efficiency, highlighting the role of management and regional context in determining performance. They assessed the efficiency of Gulf Cooperation Council (GCC) banks between 2007 and 2011 using DEA to measure technical efficiency, pure technical efficiency, and scale efficiency. Their study found that many GCC banks operate close to optimal efficiency, although there are managerial inefficiencies in resource utilization.

Stewart, Matousek, and Nguyen [44] concluded that large banks in Vietnam are more efficient than small banks, while Abedin [45] showed that both the efficiency and profitability of the banking sector in Bangladesh have a positive impact on GDP per capita, but efficiency has a smaller effect compared to profitability.

Batir, Volkman, and Gungor [46] highlights the differences in efficiency between participation and conventional banks, thus they compared the efficiency of e banks in Turkey using the DEA method and Tobit analysis for the period 2005–2013. The study showed that technical efficiency is predominant in both types of bank, suggesting that improving the technical utilization of resources can increase cost efficiency. Also, Banya and

Biekpe [47] highlighted management problems as the main source of inefficiency in banks in ten African frontier countries, suggesting the need to improve resource management. Le [48] adds the perspective that adequate capitalization improves efficiency and reduces risk, complementing Abedin's [45] study by highlighting the importance of capital in improving bank efficiency. Thus, the paper [48] investigated the technical efficiency, bank risk, and capitalization in Vietnamese banks between 2007 and 2011 using DEA. The study found that banks with higher capital are more efficient and have lower bank risk, emphasizing the importance of compliance with international capital standards such as Basel III. The results suggest that appropriate regulation can promote better use of financial resources, thereby improving banking efficiency.

In contrast, Ofori-Sasu et al. [49] concluded that the entry of foreign banks into Ghana had a negative impact on efficiency, which emphasizes the importance of efficient management in a competitive environment. Further, Kumar et al. [50] observed that Indian private sector banks exhibited high performance variance correlated with efficiency scores, suggesting a link between efficiency and risk. Recent studies, such as those by Yin [51] and Huang, Liang, and Chu [52], have emphasized the influence of business diversification and social responsibility on efficiency. On the other hand, Takahashi and Vasconcelos [53] emphasized the negative impact of non-performing loans on the efficiency of banks in Brazil, while Ayadi et al. [54] demonstrated that business models significantly influence efficiency.

The literature on the effects of socio-political factors and the quality of political-economic institutions on bank performance and efficiency remains limited and with mixed results. In this context, a recent study [55] investigated the influence of democracy and economic freedom on bank performance in European Union countries, using data from 27 countries for the period 2001–2020. Its results showed that democracy is positively associated with bank performance, while economic freedom affects it negatively, thus highlighting the impact that institutional structures can also have on bank efficiency, especially in developed economies.

Thus, the results suggest that an integrated approach, which considers both internal and external factors, is essential to improve bank efficiency in different economic environments.

2.2. Enhancing Banking Sector Efficiency Through Industry 4.0 Innovations

The COVID-19 pandemic has accelerated the transition to digitalization in the banking sector, having a significant impact on its efficiency. The studies by Al Mamun et al. [56] and Bele et al. [57] show a negative effect on the technical efficiency of banks in Bangladesh and Nigeria, respectively, as a result of the changes brought about by the pandemic. Similarly, Boubaker et al. [58] suggest that Islamic banks in ten countries have been able to maintain their efficiency by reducing their inputs in the face of crisis challenges. In addition, Mateev et al. [59] emphasize the importance of efficiency and market competition in banks' performance, stressing the need for regulatory reforms that support the sector in this tumultuous period.

Thus, Liu, Naveed, and Mustafa [60] highlight the importance of internal factors and digitalization on bank efficiency. In this regard, a recent study has examined the impact of digitalization on banks in Pakistan over the period 2006–2020. The results show that digitalization has a positive effect on bank efficiency, with variables such as return on assets and bank size positively correlated with efficiency. In addition, banks with low initial levels of efficiency have experienced significant improvements in performance through the adoption of digital technologies, which contributes to reducing efficiency disparities and creating a more balanced banking sector. These findings are relevant in the context of assessing the impact of digitalization strategies on bank efficiency in the Industry 4.0 era.

According to a study by Xingzi et al. [61], digital transformation has a significant impact on the profit efficiency of commercial banks in China, showing that a digital transformation index constructed using the entropy method positively correlates with profit efficiency. This research highlights that digitalization contributes not only to revenue

growth but also to operational cost reduction, thereby strengthening the financial performance of banking institutions.

Another study by Manta et al. [62] outlines that digitalization of the banking sector in central and eastern European countries (CEECs) has a significant impact on banking efficiency, with Romania, Latvia, and Lithuania leading the way due to substantial investments in infrastructure and customer engagement. The results indicate that digitalization improves banking performance (ROE), while countries with a saturated market, such as Hungary and Poland, require additional innovation to support continued growth. The study highlights the importance of continued investment in digitalization to increase the efficiency of the banking sector and boost economic competitiveness in the context of Industry 4.0.

The literature emphasizes that efficiency in the banking sector is key to promoting environmental sustainability, and digitalization strategies play a fundamental role in this process, especially in the context of Industry 4.0. Recent studies, such as those conducted by Elkhayat et al. [63], suggest that, through digital transformation, banks not only improve their operational performance but also become better able to allocate resources to initiatives that contribute to green cities and achieve sustainable development goals [64]. In this context, research by Manta et al. [65] and Kovac et al. [66] highlights the importance of accessibility of digital banking services to support financial inclusion, a key factor in facilitating sustainable and equitable economic development in urban areas, which directly correlates with the effectiveness of banks in the Industry 4.0 era.

Digital transformation influences not only the banking sector but also the efficiency of operations in the context of Industry 4.0. The study by Song et al. [67] highlights how digital tools enable banks to optimize the use of resources and reduce waste, which are key to increasing efficiency. Apriantoro et al. [68] emphasize that integrating sustainability principles into banks' digital strategies is important for achieving efficiency and innovation goals. Other authors [69] propose that sound governance and efficient digital operations are vital to support sustainable development projects.

Due to increased banking efficiency through digitalization, the influence of digital banks on urban sustainability goes beyond smart cities, also addressing issues of energy consumption and development in peri-urban areas. Pan et al. [70] point out that banks can stimulate investment in energy efficient infrastructure, and Sahana et al. [71] identify that bank digitalization can support sustainable development in these regions through tailored financial solutions. In addition, Meghișan-Toma et al. [72] and Bădîrcea et al. [73] show that digitalization in banking and sustainability-oriented financial strategies contribute to banking efficiency in the context of Industry 4.0, facilitating investments in green projects and supporting sustainable urban transformation [74].

Moreover, the advancement of artificial intelligence (AI) and artificial intelligence of things (AIoT) has influenced discussions on smart cities and the banking sector, generating new insights on increasing banking efficiency [75]. Similarly, Zaidi et al. [76] used bibliometric mapping and network analysis to investigate AI applications in sustainable smart cities, concluding that AI-based digital banking systems can significantly increase resource allocation efficiency and support green practices in urban environments. Likewise, Bibri et al. [77] emphasize the importance of AIoT solutions for the environmental sustainability of smart cities, and banks, through digital transformation, are well positioned to support these initiatives through financial mechanisms aligned with environmental goals.

The review of the existing literature on bank efficiency reveals some significant gaps and provides relevant directions for future research. Much of the research focuses on assessing bank efficiency in a national context, without exploring cultural, economic, and regulatory differences across economies at the regional or global level. This limitation creates a gap in the literature, preventing a comparative understanding of banking efficiency from an Industry 4.0 perspective. Future research should investigate to what extent the adoption of digitalization and Industry 4.0-specific technologies—such as artificial

intelligence and blockchain—is influenced by the economic and regulatory particularities of each region.

Despite a growing number of studies addressing digitalization in the banking sector, few analyses directly examine the influence of Industry 4.0 on bank efficiency. Many studies focus on financial performance without analyzing operational efficiency and costs in detail. There is a need for more detailed research examining how digital innovations affect the costs and efficiency of banking resources, particularly in less developed or frontier economies where technology adoption may face unique challenges.

To address these gaps, future research should broaden the geographic scope of study and standardize assessment methodologies, including benchmarking analyses that take into account the economic and technological specificities of each region. At the same time, more attention should be paid to how Industry 4.0 can support banking resilience, especially in the context of the current global economic challenges. These directions will contribute to a clearer picture of banking efficiency in the digitalization era and to practical recommendations for improving the performance of financial institutions.

3. Materials and Methods

Bibliometric methods fulfill two essential functions: performance analysis and scientific mapping [78]. Through performance analysis, the efficiency of researchers and institutions in terms of research and publication activity is assessed. On the other hand, science mapping aims to reveal the structure and dynamics of scientific domains. These data are useful for researchers when they want to investigate a particular line of research. Bibliometric methods introduce quantitative rigor into an otherwise subjective evaluation process, providing concrete evidence to support the theoretical categories derived from data analysis. In this context, bibliometric analysis has become an essential tool for studying and understanding the evolution and structure of scientific fields.

Also, bibliometric analysis is a valuable research method for elucidating the nexus between digital transformation, banking efficiency, and sustainability goals. In a similar vein, Hamman [79] has employed bibliometric methodologies to investigate the evolution of urban sustainability definitions, thereby establishing a foundation for subsequent studies. Gatto et al. [80] further developed this line of inquiry with a bibliometric study of the sustainability, development, and impact of the global pandemic caused by the SARS-CoV-2 virus, demonstrating how the pandemic has reshaped the discourse surrounding digital transformation and urban sustainability. Furthermore, Popescu et al. [81] and Abagiu et al. [82] investigated the potential of technological advances in robotics and computer vision, demonstrating how these developments could be incorporated into digital banking solutions to facilitate urban development initiatives.

Moreover, Mishra et al. [83] have conducted a bibliometric analysis of the Sustainable Development Goals (SDGs), elucidating the challenges and opportunities of achieving these goals through digital banks. The authors contend that, while digital banking can facilitate the financing of the SDGs, there are still considerable obstacles to be overcome, including technological constraints and disparities in access to digital services. This perspective is consistent with the broader discussion by Kovac et al. [66] on the digital divide in Europe. It is therefore evident that addressing these disparities is essential for banks to play an effective role in sustainability goals.

VOSviewer version 1.6 18, a specialized software, facilitates such bibliometric analyses. This program allows the creation and exploration of maps based on network data. According to the VOSviewer manual, the software generates maps based on several types of data, such as the adjacency matrix of a network, scientific publications and journals, researchers, research organizations, countries, or keywords, by analyzing co-authors, co-occurrences, citations, bibliographic links, or co-citation networks extracted from databases such as Web of Science, Scopus, PubMed, or RIS. These techniques allow the analysis of keywords, authors, institutions, and countries, highlighting the most frequently cited authors and top research centers.

In addition, bibliometric analysis also assesses the impact of a publication in the scientific community and the reputation of the author [84]. According to Zupic and Tomaž [85], this type of analysis helps to review the literature, guiding researchers to influential works and objectively mapping the field of study.

In this study, we conducted a bibliometric analysis of resources in the Web of Science and Scopus databases, including academic articles and relevant publications, to identify the main trends, connections, and developments in the use of the concept of "efficiency" in the banking sector. We used these two databases because each brings a distinct value: the Web of Science provides extensive coverage of high-quality academic publications globally, while Scopus includes a broader spectrum of recent studies, with an emphasis on regional diversity and novel perspectives. We have restricted the selection to publications in the financial–economic domain, thus ensuring that we analyze articles directly relevant to the banking sector. In the end, we obtained a sample of 9007 articles in Web of Science and 4316 articles in Scopus, which allowed us to explore the concept of efficiency in the banking context in more depth and to identify key issues for our study.

Figure 1 outlines the essential steps for conducting a bibliometric analysis of the term "bank efficiency" using the Web of Science and Scopus databases. In our study, the research process begins with the identification, selection, and filtering of relevant articles, followed by the downloading and importing of data for comprehensive analysis. In the final stage, we analyze the selected articles through the use of co-occurrence maps, focusing on keywords, co-authorship connections, institutional collaboration networks, and mapping of specialized journals.

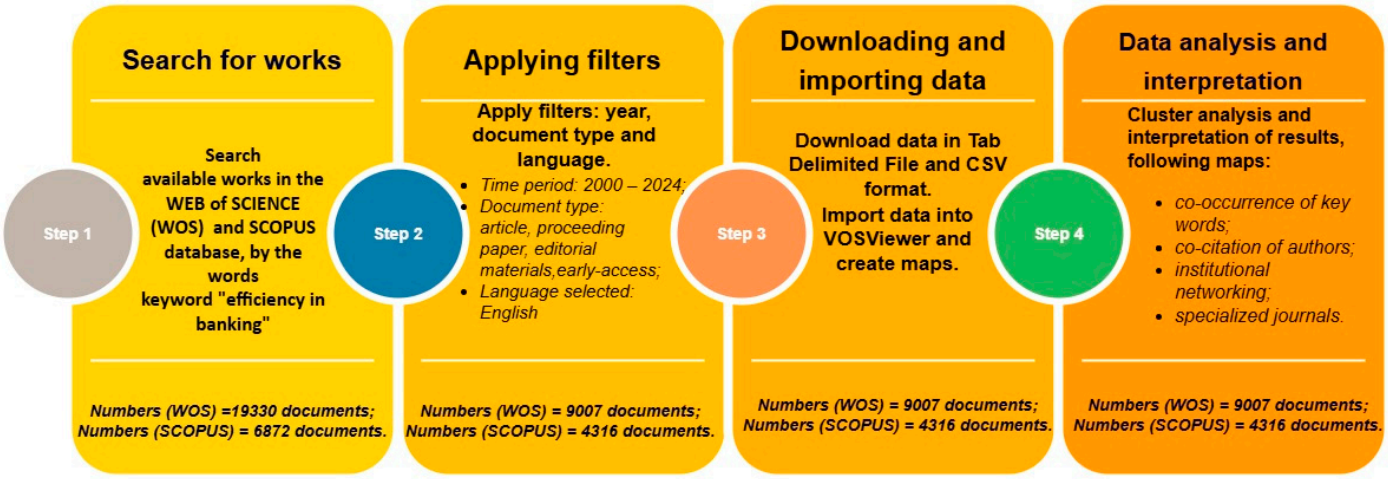

Figure 1. Methodological steps in bibliometric analysis. Source: own processing.

4. Results

This section focuses on the RQ1 approach by analyzing the evolution of published scientific articles on bank efficiency in the context of Industry 4.0 over the selected period (Figure 2). The evolution of the number of publications over time is detailed in the analysis below. The term "efficiency" in banking started to be significantly used in Web of Science articles in 1978, initially marked by sporadic and incipient interest. However, a significant increase in the use of this term has been observed since the year 2000, reflecting an intensification of concerns about efficiency in the banking sector. This upward trend has continued to grow steadily, reaching a peak of 739 articles published in 2021, highlighting a continued and increased interest in research and development in this area.

We observe significant increases in the number of publications in certain periods. In particular, between 2004 and 2005 we identified an almost immediate doubling in the number of publications, from 85 to 138. Likewise, between 2014 and 2016 we noted another significant increase, from 401 to 512 publications. However, after 2021 we observed a

significant decrease in the number of publications. In 2022, the number dropped to 323, and in 2023 the number increases significantly, reaching 591 articles.

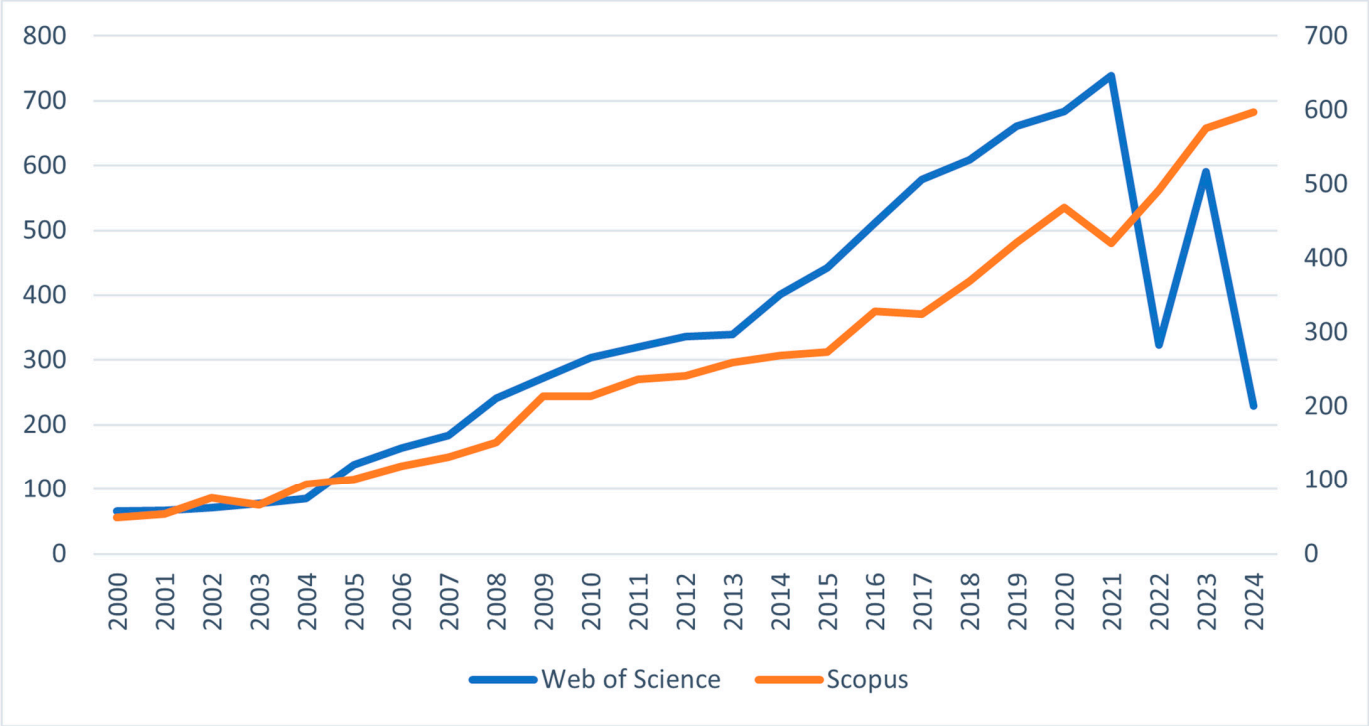

Figure 2. Publications on efficiency in banking. Source: Web of Science and Scopus, 2024.

These changes can be attributed to socio-economic and global factors. For example, the significant fluctuations in interest in efficiency may be associated with economic crises, which have considerably sharpened the focus on efficiency in the banking sector, such as, for example, the 2008 global financial crisis. In contrast, recent declines could be influenced by factors such as the COVID-19 pandemic and changes in research priorities as financial institutions have focused more on crisis management and adapting to new economic conditions.

However, in the analysis of the publications in the Scopus database on the topic of bank efficiency, there has been a steady increase in the number of articles since 2000, when only 49 papers were published. By 2010, the number of publications gradually increases to 214, indicating a moderate interest in the topic. Between 2011 and 2015, the number of articles continues to increase, reaching 273 papers in 2015, reflecting the increased concern for banking efficiency in the context of the global financial crisis. After 2016, there is an accelerated increase, peaking at 468 articles in 2020, likely influenced by the rapid digitalization of the banking sector. In 2024, Scopus records a new high of 597 publications, indicating high interest in analyzing banking efficiency in the context of new technologies and sustainability.

Looking at the trajectory of academic publications, there has been a continuous growth of interest in this topic, with an increasing number of articles published in major databases such as Scopus and Web of Science. In the early 2000s, the number of papers was relatively low, but in the decades that followed the number of publications increased significantly, reflecting the growing relevance of bank efficiency in an increasingly complex and globalized financial environment.

4.1. Co-Compete Network Analysis of Keywords

This section focuses on the RQ2 approach by analyzing the keywords in the relevant scholarly works needed to identify the key themes and sub-domains explored in studies on banking efficiency in the context of digitalization and Industry 4.0.

This analysis provides insight into the topics and issues that have attracted the most attention from researchers in this area. By identifying keywords that appear together frequently in the papers included in the analysis, it is possible to highlight the dominant themes and connections between the concepts addressed in bank efficiency research. This information can be valuable to researchers, providing them with a deeper understanding of the prevailing research directions and the relationships between different aspects of efficiency in banking. Therefore, keyword co-occurrence network analysis can be a powerful tool for identifying trends and guiding future research in this area, contributing to the development of a more comprehensive knowledge base and improving our understanding of efficiency in the banking sector.

The purpose of the keyword co-occurrence network analysis is to identify and evaluate terms that have been frequently used in the efficiency literature in the banking sector. As a result of this analysis, eight distinct clusters were identified, each with its own characteristics (Figure 3).

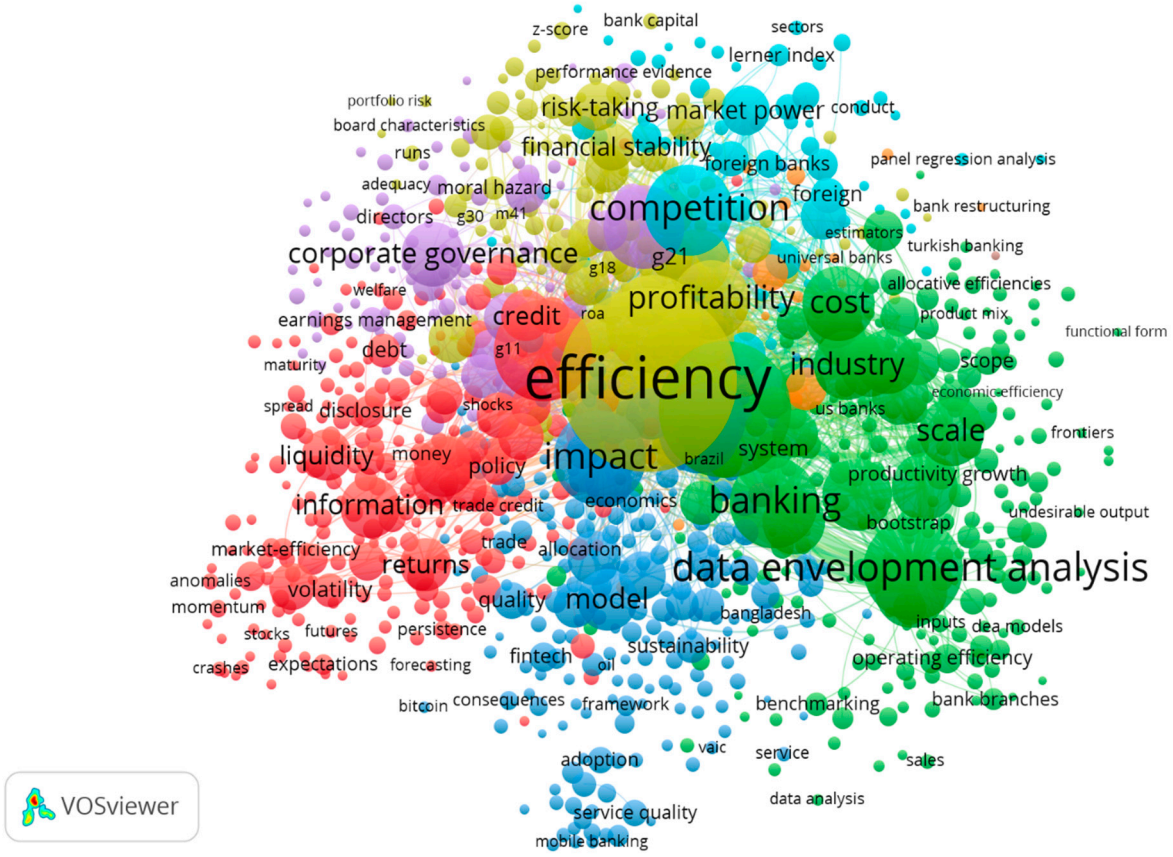

Figure 3. Keyword co-occurrence network in Web of Science database. Source: own processing in VOSviewer.

First, the red cluster includes a total of 242 items. The central and most significant node in this cluster is "risk", which shows 7300 strong links. In addition to the "risk" node, this cluster includes other relevant nodes such as "information", "returns", "liquidity", and "market". The green cluster, with 221 items, has "performance" as its main node, which stands out with a remarkable 14,105 links. Other important nodes in this cluster are "banking", "data envelopment analysis", "scale", "industry", "cost", and "productivity".

On the other hand, the blue cluster comprises 201 items and includes significant nodes such as "impact", "model", "sustainability", "fintech", "technology", and "quality". Similarly, the lime green cluster is centered on the term "efficiency", with 3104 occurrences and 21,858 strong links. This cluster contains a total of 144 items and emphasizes the significant relevance of the concept "efficiency" in the literature.

Further, the purple cluster includes important nodes such as "competition", "corporate governance", "market power", and "ownership structure". These nodes suggest that studies focus on the impact of competition and governance on bank performance and stability, as well as market power and ownership structure.

In contrast, the orange cluster contains 25 items and is one of the smallest clusters with limited relevance. In addition, the brown cluster is the smallest, with only two items and is considered of marginal relevance in bibliometric analysis.

These are the results of a keyword co-occurrence analysis extracted from the Scopus database (Figure 4), applied to a set of publications in the field of banking. The resulting bibliometric map reflects the structure and dominant themes in research in this field by highlighting frequently used keywords and the connections between them. As a result of the analysis, 12 distinct thematic clusters of 9796 words were identified, each representing a specific area of research interest in the topic of bank efficiency.

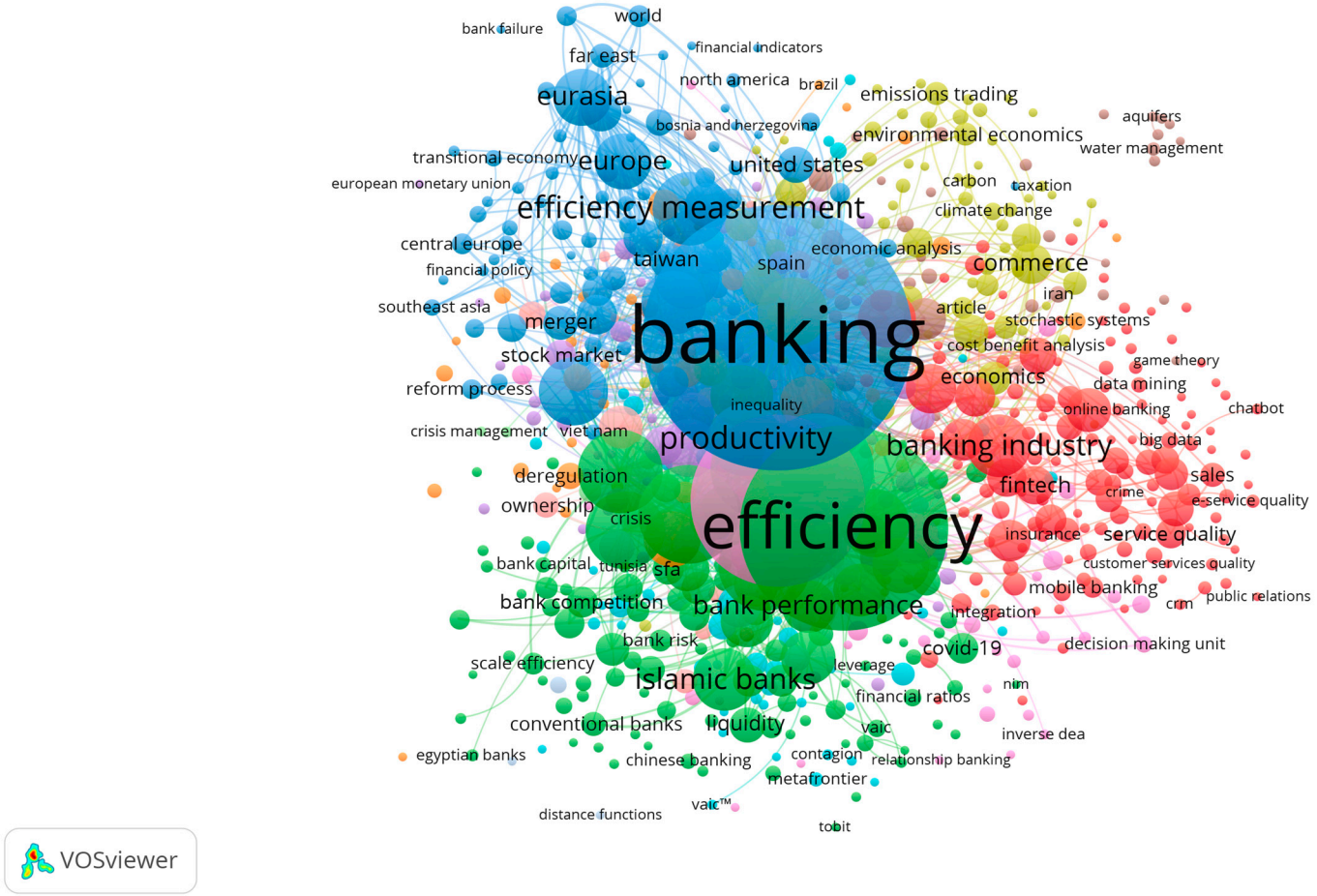

Figure 4. Keyword co-occurrence network in Scopus database. Source: own processing in VOSviewer.

First of all, the central importance of the terms "banking" and "efficiency" stand out, occupying central positions and having considerable dimensions in the map. This underscores their fundamental role in research in the field, as they are the most frequently encountered keywords in the analyzed dataset. According to the results, the term "banking" appears 978 times and has the highest link strength ("total link strength" of 5393), followed by "efficiency", which appears 652 times and has a link strength of 2791. These figures demonstrate their central position and their role in linking various banking research themes and topics.

Second, the thematic distribution of clusters provides insight into current concerns in banking research. The blue cluster, for example, explores issues related to the global economy and international financial markets. Key terms in this cluster include "Europe",

"United States", "financial system", and "efficiency measurement", suggesting a macroeconomic and comparative approach to banking systems across geographic regions. This thematic distribution indicates researchers' interest in analyzing and comparing banking performance internationally.

The green cluster also brings to the fore topics such as "crises", "bank performance", and "Islamic banks". It illustrates the concern with measuring and evaluating bank efficiency, using specific methods to analyze cost and technical efficiency. In the context of bank efficiency studies, "data envelopment analysis" (DEA), which appears 495 times, is one of the most used methods to assess the performance of financial institutions. This highlights the importance of quantitative methods in analyzing bank performance.

Next, the red cluster reflects the impact of emerging technologies on the banking sector, including terms such as "big data", "decision making", and "customer satisfaction". This theme indicates a clear trend toward digitalization and a growing focus on customer experience and decision-making processes assisted by modern technologies such as big data analytics.

Another notable cluster is the yellow cluster, focused on themes of sustainable development and green economy. Terms such as "sustainable development", "environmental economics", and "emissions trading" suggest a growing concern for sustainability in the financial sector and the role of banks in the transition to a green economy. This theme also reflects the alignment of the banking sector with global environmental and sustainability requirements, which have intensified in recent decades.

Moreover, the network structure of the map indicates a strong interconnectedness between the various themes, especially around the core terms. This density of connections suggests a well-linked literature and a significant interdependence between research topics in banking, reflecting the complexity and interconnectedness of current issues in the field.

The keyword analysis of the Scopus database highlights the diversity of themes and concerns in banking research. While efficiency and performance remain central themes, there is a progressive integration of technological innovations and sustainability concepts. This bibliometric map thus highlights how the field of banking is evolving, combining traditional performance management approaches with new demands to adapt to digital technologies and global environmental responsibilities.

4.2. Authors' Co-Citation Network

In the context of analyzing efficiency in the banking sector, it is essential to understand which authors have significantly contributed to this topic, both through the volume of published works and their academic impact, as measured by citations. Thus, RQ3 focuses on identifying the most cited authors in studies on banking efficiency, reflecting their influence on specialized literature. In parallel, RQ4 explores the most prolific authors on this topic, providing insight into researchers' productivity and the ways in which they have expanded knowledge in this field.

The bibliometric analysis performed through the VOSViewer application allows the identification of the most highly cited authors in a given research field, taking into account both their direct citations and co-citations in various publications. This type of analysis is necessary to highlight the most influential authors in the field, providing a tool for exploring and understanding trends in academic research. The method provides a detailed insight into the significant contributions of authors and collaborative networks in the field, thus facilitating the process of synthesizing and orienting the literature.

In the bibliometric analysis performed, a rigorous selection was applied to identify the most influential authors in a specific field. This selection required that each author had at least five published papers and had been cited at least once in the literature. By applying these criteria, out of a total of 16,170 original authors, only 381 were selected who fulfilled these conditions.

Authors were grouped into 21 distinct clusters, each with a central node representing a lead author within that cluster (Figure 5). The clusters have between 2 and 25 members,

reflecting authors' collaborative networks and influence on research directions. Researchers such as Molyneux, Philip, Matousek, Roman, and Hassan, M. Kabir are recognized as central nodes in the research network, indicating a significant contribution to the field of bank efficiency. Other influential authors include Tsionas, Mike G., Tan, Yong, and Sufian, Fadzlan, who have important roles in studies of the performance of financial institutions. The network density in the core area reflects high interconnectedness among researchers studying bank efficiency, underscoring the continuing intense research in this critical area. Regional clusters were also observed, such as the green cluster, led by Sufian, Fadzlan and Kamarudin, Fakruddin, indicating a geographic focus on regions such as Southeast Asia. The light blue cluster, which includes researchers such as Lee, Chien-Chiang and Huang, Tai-Hsin, suggests interest in other regions or specific sub-domains of bank efficiency. Authors placed at the fringes of the network, such as Lin, Chen, Dong, Yizhe, and Zhu, Joe, suggest less involvement in central collaborations, focusing on specific research niches. In addition, emerging collaborative networks, such as those developed by Emrouznejad, Ali, and Lu, Wen-Min, indicate the emergence of innovative directions in bank efficiency research.

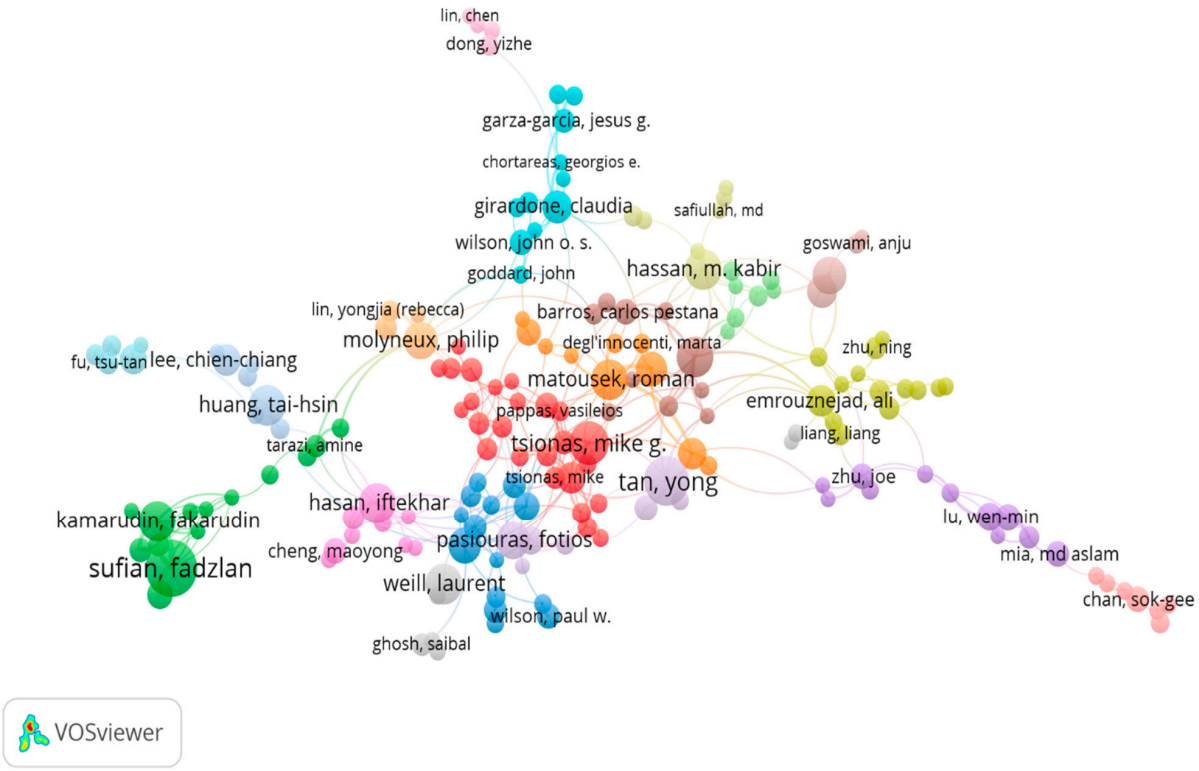

Figure 5. Co-citation of authors in Web of Science database. Source: own processing in VOSviewer.

In terms of the number of publications, Fadzlan Sufian was identified as the author with the most papers in the field of bank efficiency (Table 1), with 56 papers published, followed by Yong Tan, with 42 papers, and Mike G. Tsionas, with 33 papers. This reflects a steady and significant contribution to the literature.

The citation ranking shows that An Berger is the most cited author, with 7151 citations, followed by Db Humphrey and R Levine, with 2815 and 2626 citations, respectively. Other influential authors in terms of citations are Leopold Simar, Paul W. Wilson, and Lj Mester, which confirms the impact of their work in assessing bank efficiency and performance.

In Figure 6, the network map made up of keywords from the Scopus database, several key elements stand out, which we will analyze below. The analysis resulted in 51 distinct clusters, meaning that out of a total of 3951 authors, only 51 met the criterion of having at least three papers published.

Table 1. Important authors by documents and citations in Web of Science database.

Ranking	Authors of Documents	Documents
1	Sufian, Fadzlan	56
2	Tan, Yong	42
3	Tsionas, Mike G.	33
4	Wanke, Peter	29
5	Matousek, Roman	29
6	Huang, Tai-hsin	29
7	Kamarudin, Fakarudin	28
8	Hasan, Iftekhar	28
9	Chiu, Yung-Ho	28
10	Hassan, M. Kabir	28
Ranking	**Authors of Documents**	**Citations**
1	Berger, An	7151
2	Humphrey, Db	2815
3	Levine, R	2626
4	Simar, Leopold	2444
5	Wilson, Paul W.	2428
6	Mester, Lj	2169
7	Molyneux, Philip	1813
8	Pasiouras, Fotios	1730
9	Lovell, Cak	1534
10	Hasan, Iftekhar	1479

Source: own processing, data processed in the VOSviewer program.

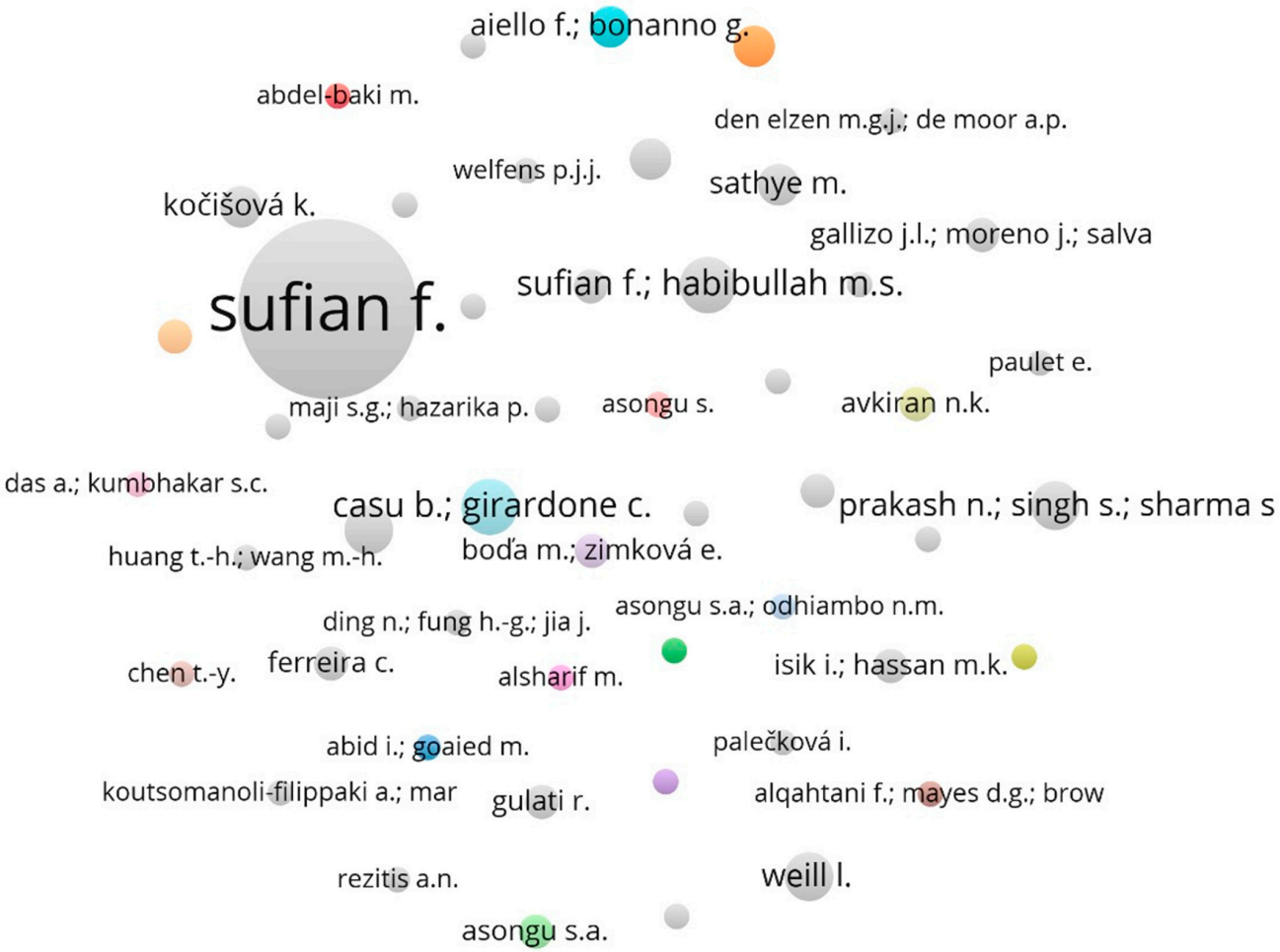

Figure 6. Co-citation of authors in Scopus database. Source: own processing in VOSviewer.

First, central and influential authors stand out by their position in the network. For example, Sufian F. appears as a central node, being connected to many authors. This suggests that Sufian F. is a reference author in the field, with 25 papers and 566 citations. His central position undoubtedly reflects frequent collaborations or a strong influence on the literature. On the other hand, another important author, Casu B., together with Girardone C., form an influential cluster. With 7 papers and 676 citations, Casu B. proves to be a significant contributor, indicating a substantial contribution to knowledge in this area.

Another aspect to note is the clustering and subdomains of the research. The map suggests the existence of several clusters of authors, each with a distinct specificity. For example, the green cluster, dominated by Sufian F., seems to be associated with research oriented towards the measurement of bank efficiency, given the high interest in specific methods such as data envelopment analysis (DEA). In contrast, the blue cluster, formed around the authors Casu B. and Girardone C., indicates a more applied orientation towards competitiveness and efficiency issues in European commercial banks, contextualized by the terms associated with these authors. Other clusters, such as that of the authors Weill L. and Tan Y., are more on the periphery of the network, suggesting specific sub-domains, perhaps oriented towards regional case studies or concrete issues of efficiency and performance in the banking sector.

In terms of links between authors and their collaborations, the strong connections between Sufian F. and other authors, such as Habibullah M.S., suggest intensive collaboration and frequent co-authorship in papers dealing with banking efficiency. These collaborations are essential for the development of a consolidated and well-represented research field. In contrast, the lower connectivity of marginal authors, such as Kočišová K. or Aiello F., indicates that they contribute to the field, but without forming extensive network links. These authors may have a specific impact on niche topics or individual studies, but without being part of an extensive network of co-authors.

Citation power and academic relevance are also important aspects to consider. Casu B. and Girardone C. enjoy the highest number of citations, 676 (Table 2), reflecting a high level of academic recognition and considerable influence in the field. These authors are undoubtedly cited for papers discussing efficiency and competitiveness in the banking sector. Other authors with a high citation frequency, such as Sufian F. (566 citations) and Tan Y. (546 citations), reinforce the idea that they have a significant contribution and are known for innovative methodologies or insights in banking.

Table 2. Important authors by documents and citations in Scopus database.

Ranking	Authors of Documents	Documents
1	Sufian F.	25
2	Casu B.; Girardone C.	7
3	Sufian F.; Habibullah M.S.	7
4	Prakash N., Singh S.; Sharma S.	6
5	Tan Y.; Floros C.	6
6	Weill L.	6
7	Aiello F.; Bananno G.	5
8	Al-Obaidan A.M	5
9	Kočišová K.	5
10	Sathye M.	5
Ranking	**Authors of Documents**	**Citations**
1	Casu B.; Girardone C.	676
2	Isiki I.; Hassan M.K.	590
3	Sufian F.	566
4	Tan Y.; Floros C.	546
5	Weill L.	450
6	Avkiran N.K.	420
7	Sathye M.	319

Table 2. *Cont.*

Ranking	Authors of Documents	Documents
8	Kao C.; Liu S.-T.	256
9	Abdul-Majid M.; Saal D.S.; Battisti G.	191
10	Koutsomanoli-Filippaki A.; Margaritis.	176

Source: own processing, data processed in the VOSviewer program.

4.3. Collaborative Institutional Analysis of Co-Authors

To gain a better understanding of the key players in banking efficiency research, it is essential to identify the institutions that have made significant contributions to this topic. Thus, RQ5 focuses on highlighting the research institutions that have investigated and published relevant work on efficiency in the banking sector, providing an overview of the centers of excellence and research networks that have advanced knowledge in this field.

The bibliometric analysis of data on organizations and the number of publications and citations associated with them provides a detailed insight into institutional contributions to the field of efficiency in the banking sector. These institutions were selected based on the large number of papers published and their research impact. Through their outstanding contributions to the field, these institutions play an important role in generating relevant and valuable results, reinforcing their position as leaders in the field of banking efficiency.

Figure 7 reflects an analysis based on a minimum threshold of five published papers and a minimum of one citation for each institution. As a result of this analysis, we have obtained a ranking consisting of 27 clusters, which highlights the distinct contribution of each institution to efficiency research in banking. Only 869 institutions met these criteria out of a total of 5471, underlining their considerable commitment and impact in this growing field.

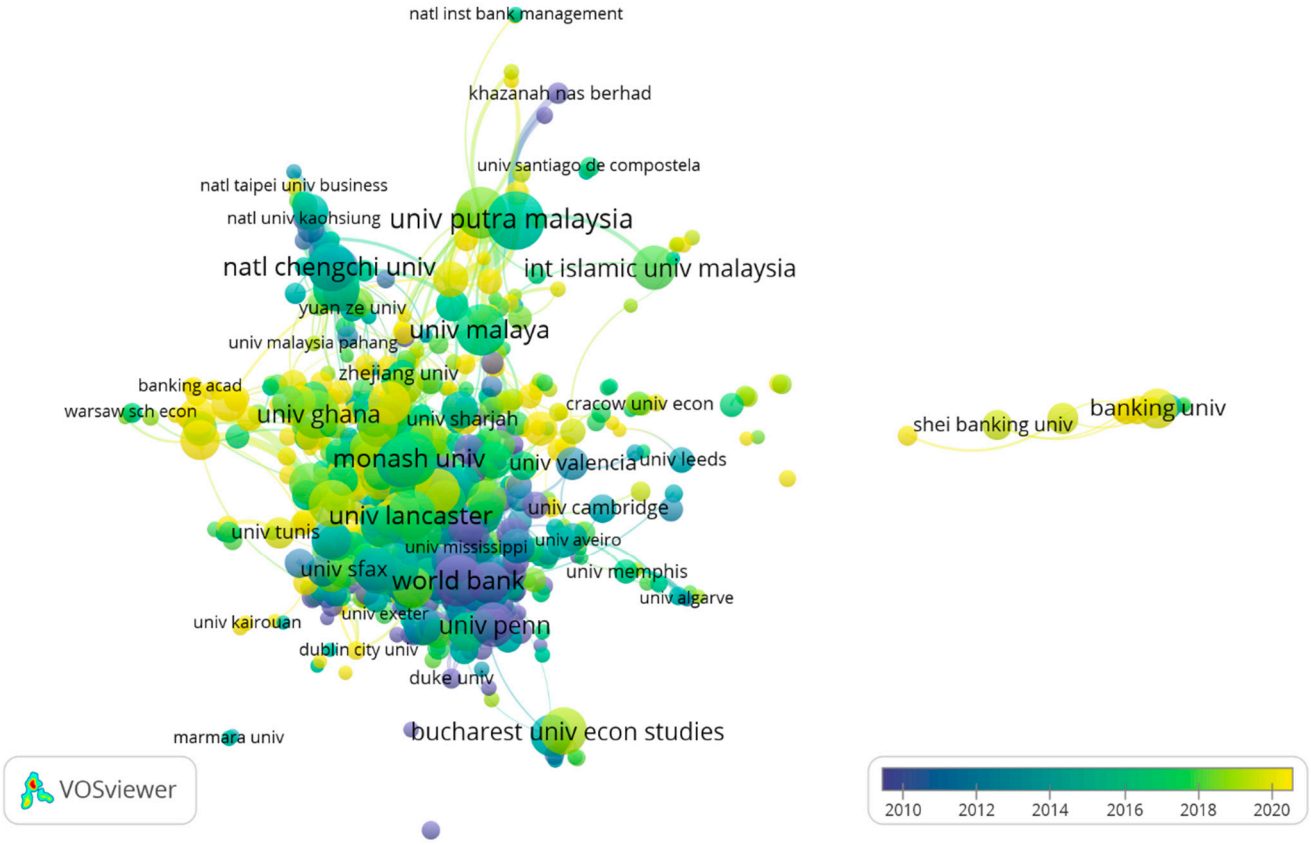

Figure 7. Institutional co-author network in Web of Science database. Source: own processing in VOSviewer.

The map of collaboration (Figure 7) between various academic institutions and organizations based on their co-citation or collaboration in the field of banking efficiency research highlights several relevant aspects. The largest nodes are represented by the following core institutions: "University Putra Malaysia", "University Malaya", and "International Islamic University Malaysia" are among the most prominent, suggesting a significant contribution in the research network. "World Bank" also appears as a central node, indicating considerable influence in research collaborations. The central part of the map is densely populated, indicating that a large number of closely collaborating institutions, such as "University Ghana", "Monash University", "University Lancaster", "University Lancaster", "University Penn", and "Bucharest University Economic Studies", are located near the center, signaling a high degree of collaboration. And peripheral institutions at the edge of the network, such as "University Sao Paulo University" and "Marmara University", suggest that they have fewer direct links compared to the central ones. These institutions might be newer in the field of bank efficiency research and are smaller in number.

Thus, the evolution over time is represented by the color of the dots, which vary from blue to yellow, indicating a temporality of the collaborations. Yellow dots represent more recent collaborations (2016–2020), while blue dots indicate older collaborations (2010–2012).

There are distinct regional sub-networks such as those in Southeast Asia (e.g., Malaysia) and Europe (e.g., "University Lancaster", "University Cambridge"), suggesting that collaborations are also influenced by geographical proximity, thus suggesting that collaborations between institutions in the same geographical region are more frequent and potentially closer than those between institutions in different regions.

The analysis of these data emphasizes that central institutions such as "University Putra Malaysia" and the "World Bank" have a major impact on research in the field, with many publications and citations (Table 3). "World Bank" stands out, with an impressive number of citations, reflecting its significant influence on the literature. In contrast, institutions with many publications but relatively fewer citations, such as "University Putra Malaysia", suggest a wider distribution of research, but with an average impact of each paper. This diversity in institutional contributions provides a comprehensive picture of the influence and network of research on bank efficiency.

Table 3. Top 10 universities by number of affiliated publications published in Web of Science database.

Ranking	Organization	Publications	Citations
1	University Putra Malayesia	75	1464
2	Monash University	66	1892
3	University Utara Malayesia	61	922
4	University Malaya	60	1068
5	World Bank	60	8431
6	University Lancaster	57	1034
7	University Nottingham	55	1806
8	National Chenghi University	54	786
9	University Ghana	53	851
10	University Essex	52	2144

Source: own processing, data processed in the VOSviewer program.

Analyzing the institutions that have significantly contributed to banking efficiency research, based on data from Scopus, we observe a structure organized into three distinct clusters, each representing different academic and research networks with varied influences on the field.

The first cluster (Figure 8), marked in green, is dominated by institutions such as Auburn University and the Milken Institute in the United States. This connectivity suggests important collaborations and an indirect influence, even in the absence of a high volume of publications. Generally, the green cluster focuses on applied financial efficiency studies, offering practical solutions and models for assessing banking performance, thereby contributing to the development of applied research directions.

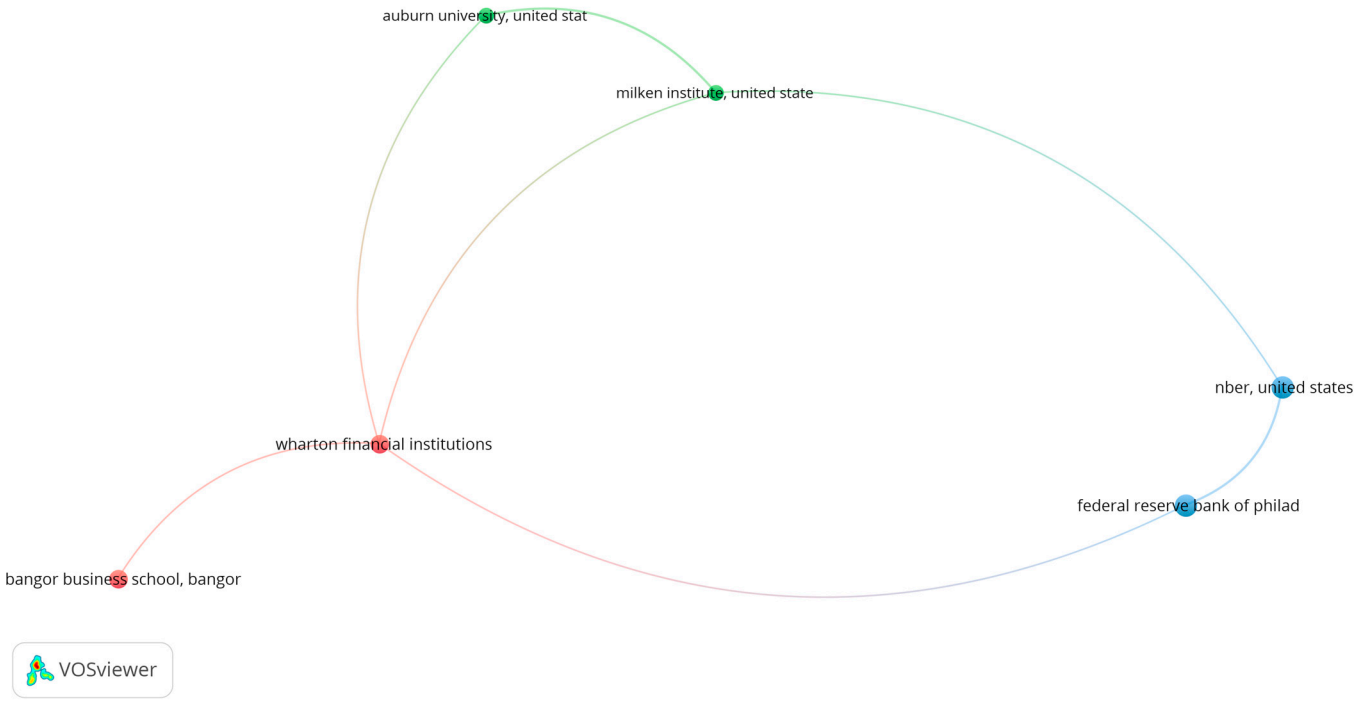

Figure 8. Institutional co-author network in Scopus database. Source: own processing in VOSviewer.

In contrast, the blue cluster includes prominent institutions in the field, such as the National Bureau of Economic Research (NBER) and the Federal Reserve Bank of Philadelphia, which have a significant impact on research in this area. These institutions stand out due to their high citation counts: NBER has five works, with a total of 1399 citations, while the Federal Reserve Bank of Philadelphia has 189 citations (Table 4) from the same number of documents. These figures highlight the role of these organizations in shaping macroeconomic research and economic policy, particularly through studies focused on banking efficiency at both national and international levels. Therefore, the blue cluster makes an essential contribution to both theoretical development and empirical approaches in the field, serving as a central pillar of the specialized literature.

Table 4. Top 10 universities by number of affiliated publications published in Scopus database.

Ranking	Organization	Publications	Citations
1	University Putra Malayesia	8	60
2	Kazan Federal University	7	13
3	International Islamic University Malaysia	6	90
4	University of New Orleans	6	691
5	Vietnam National University	5	76
6	Islamic Azad University	5	23
7	Federal Reserve Bank of Philadelphia	5	189
8	NBER, United States	5	1399
9	Bank of Finland	5	513
10	University of Surrey	5	76

Source: own processing, data processed in the VOSviewer program.

On the other hand, the red cluster includes European and international institutions such as Bangor Business School and the Wharton Financial Institutions Center, which have a notable impact in the literature on banking efficiency. According to the table data, the Wharton Financial Institutions Center has published four documents, accumulating a total of 228 citations, which grants it substantial influence in comparative studies on banks' operational efficiency. The red cluster is characterized by a strong network of academic collaborations, focused on research related to managerial and operational efficiency in

banking, with a specific emphasis on the European context, thereby bringing an important regional perspective to the field.

Thus, the analysis of institutions from Scopus highlights the geographical and thematic diversity of research on banking efficiency, with each cluster reflecting a distinct network of collaboration and influence. Notably, institutions in the blue cluster, such as NBER and the Federal Reserve Bank of Philadelphia, stand out for their significant impact, as demonstrated by the high number of citations and strong connections within the global research network, positioning them as central players in the development of this field.

4.4. Analysis of Specialized Journals

To answer RQ6, we identify the leading journals that publish the most articles on efficiency in banking. This analysis highlights the key publications for researchers, providing insight into trusted sources and key contributions in the field.

In analyzing the thematic map of banking efficiency research, the Journal of Banking and Finance stands out as one of the most influential journals in the field, with a significant number of published papers (104), citations (12,375), and a very high total link strength (19,530) (Table 5). The large size of this journal's bubble in representation and its central position, with multiple links to other journals, emphasize its role as a central reference for banking efficiency research, and it is often cited and used by other researchers as a theoretical and practical basis.

Table 5. Analysis of the journals.

No.	Journal	H-Index	Quartile	Number of Articles Published	Number of Citations
1	*Journal of Banking and Finance*	197	Q1	104	12,375
2	*Bank and Bank Systems*	22	Q3	85	436
3	*Applied Economics*	113	Q2	73	2030
4	*Applied Financial Economics*	0	Q3	52	1582
5	*Managerial Finance*	48	Q2	51	904
6	*Sustainability (Switzerland)*	169	Q2	47	777
7	*Journal of Productivity Analysis*	93	Q2	38	2382
8	*International Journal of Finance and Economics*	52	Q2	37	603
9	*Economic Modelling*	111	Q1	37	1511
10	*Research in International Business and Finance*	73	Q1	36	1397

Source: own processing, using data provided by Scopus database.

A time scale (2010–2020) is shown at the bottom right of the map, suggesting that the intensity of the colors of each bubble corresponds to the period of relevance of the studies (Figure 9). Journals more recent in publishing articles on banking efficiency are represented in lighter colors (towards yellow), while those with older contributions are colored in darker tones. For example, the Journal of Banking and Finance has an intermediate shade, suggesting a consistent contribution over the entire period, indicating that the topic of banking efficiency has been recurrent and is of continuing interest to this journal.

Banks and Bank Systems and Applied Economics are also important journals in the field, with 85 papers and 436 citations, respectively, a substantial number of papers and citations. Banks and Bank Systems specializes in topics strictly related to the banking sector and is a relevant source for bank efficiency research. Journals such as Applied Financial Economics and Managerial Finance are also relevant, with a substantial number of citations and high link strength, suggesting that they are used in studies addressing various aspects of financial efficiency and bank management.

The overall link strength reflects the degree to which a journal is interconnected with others in the network, while the number of citations emphasizes its influence in the field. For example, journals with high link strength, such as the Journal of Banking and

Finance and Applied Economics, are frequently cited by other papers in the field of banking efficiency, indicating their status as fundamental sources for researchers.

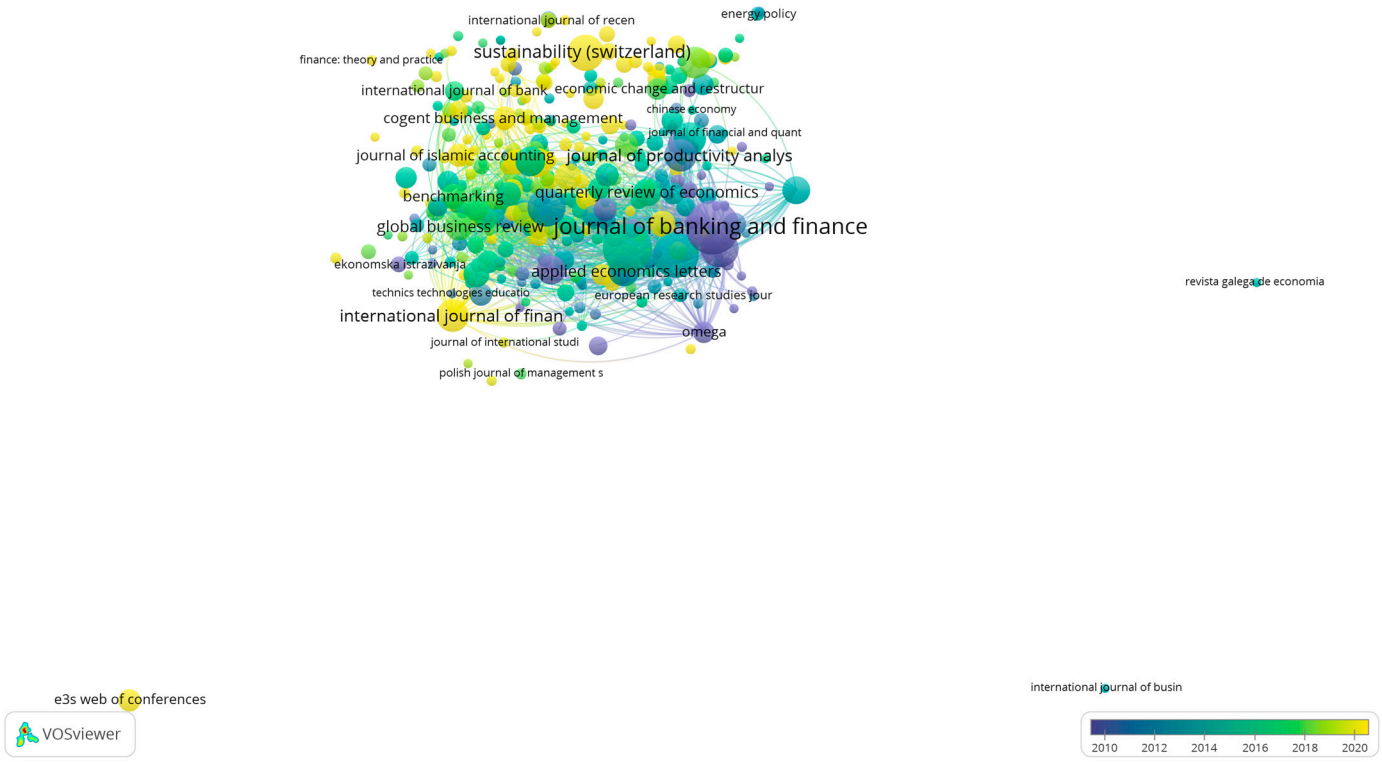

Figure 9. Mapping of specialized journals in Scopus database. Source: own processing in VOSviewer.

Sustainability (Switzerland), while having a lower number of papers and citations compared to other top journals, shows considerable link strength. This suggests a recent integration of sustainability themes into bank efficiency research, emphasizing the role of this journal in exploring the social and environmental impacts of banking.

Journals colored in yellow and light green, such as Sustainability (Switzerland) and the Journal of Productivity Analysis, indicate a focus on emerging topics such as sustainability and productivity in the banking sector, suggesting a growing academic interest in these topics. These publications are notable for addressing contemporary challenges in a changing financial landscape.

On the other hand, journals illustrated in shades of blue or purple, such as the Journal of Banking and Finance, denote essential contributions to the theoretical foundations of the field, with a steady activity over time, with relevance to both previous research and current scholarship. This suggests that, over the years, the fundamental themes in this journal have remained of interest, being a pillar of reference in the field.

The journal's interconnectivity highlights a dense network of links between recent and foundational scholarship, demonstrating how contemporary research in sustainability and efficiency in banking is integrated with the core literature in the field, represented by journals such as Applied Economics and Managerial Finance. This network structure suggests conceptual continuity and evolution, with constant adaptation to new perspectives and challenges in the banking sector.

4.5. Analysis of the Most Cited Papers

To highlight the foundational work in the field of banking efficiency, it is essential to identify the studies with the highest impact as measured by citation count. Thus, RQ7 focuses on presenting the most cited papers on the topic of efficiency in the banking sector, as these are key references that have significantly influenced the development of specialized literature.

In order to identify gaps and future directions in efficiency research in the banking sector, we conducted a thorough review and synthesis of the most influential papers on this topic. Using the same article database as in the previous bibliometric analysis, covering the period 2010–2024, we selected significant papers through a filter based on the number of citations (Table 6). We focused on articles with more than 100 citations, which allowed us to focus on the most cited and influential studies. This method helped us to identify and analyze in detail the most relevant research in the field of bank efficiency.

Table 6. List of most cited papers.

No.	Authors	Publication Title	Year of Publication	Number of Citations	Journal	H-Index
1	Beck, T.; Demirgüç-Kunt, A.; Merrouche, O.	Islamic vs. conventional banking: Business model, efficiency, and stability	2013	780	*Journal of Banking and Finance*	197
2	Fethi, M.D.; Pasiouras, F.	Assessing bank efficiency and performance with operational research and artificial intelligence techniques: A survey	2011	427	*European Journal of Operational Research*	305
3	Fiordelisi, F.; Marques-Ibanez, D.; Molyneux, P.	Efficiency and risk in European banking	2011	350	*Journal of Banking and Finance*	197
4	Barth, J.R.; Lin, C.; Ma, Y.; Seade, J.; Song, F.M;	Do bank regulation, supervision, and monitoring enhance or impede bank efficiency?	2013	295	*Journal of Banking and Finance*	197
5	Barros, C.P.; Managi, S.; Matousek, R.	The technical efficiency of the Japanese banks: Non-radial directional performance measurement with undesirable output	2012	268	*Omega*	167
6	Paradi, J.C.; Zhu, H.	A survey on bank branch efficiency and performance research with data envelopment analysis	2013	256	*Omega*	167
7	Schaeck, K.; Cihák, M.	Competition, efficiency, and stability in banking	2014	231	*Financial Management*	80
8	Chortareas, G.E.; Girardone, C.; Ventouri, A.	Bank supervision, regulation, and efficiency: Evidence from the European Union	2012	212	*Journal of Financial Stability*	73
9	Chortareas, G.E.; Girardone, C.; Ventouri, A.	Financial freedom and bank efficiency: Evidence from the European Union	2013	179	*Journal of Banking & Finance*	197
10	Staub, R.B.; da Silva e Souza, G.; Tabak, B.M.	Evolution of bank efficiency in Brazil: A DEA approach	2010	167	*European Journal of Operational Research*	305

Source: own processing, data processed in the VOSviewer program.

Thus, Table 6 highlights academic works in the field of banking efficiency, categorized by the number of citations. In first place is the study by Beck, Demirgüç-Kunt, and Merrouche [86], which, with 780 citations, examines the differences between Islamic and conventional business models, emphasizing efficiency and stability. Similarly, the paper by Fethi and Pasiouras [87], with 427 citations, provides a comprehensive review of operations research and artificial intelligence techniques in assessing bank efficiency, suggesting considerable interest in advanced analytic methods.

Another important study is Fiordelisi et al. [40], with 350 citations. This research explores the relationship between efficiency and risk in the European banking sector, a highly relevant topic in the post-financial crisis period. It argues that low levels of efficiency may encourage banks to try to increase their returns by lowering operational standards, such as less rigorous credit monitoring.

Barth et al. [88], with 295 citations, analyzes the impact of bank regulation on efficiency. The authors find that the enhanced market monitoring of banks, which includes greater financial transparency and improved external auditing, is positively associated with increased bank efficiency. Similar results are also obtained in a dynamic framework, where

the impact of changes in banking regulation and supervisory schemes on the evolution of banks' operational efficiency is analyzed, controlling for unobservables.

The papers by Barros et al. [89] and Paradi and Zhu [90] are also notable, each with over 250 citations and focusing on bank technical efficiency and performance and bank branch efficiency, respectively.

These four publications are significant in the field of banking efficiency research and have had a considerable impact, being frequently cited in the literature. Schaeck and Cihák's study [91], with 231 citations, explores the relationship between competition, efficiency, and stability in the banking sector, making it essential for understanding the dynamics of the financial sector. The works of Chortareas et al. [92,93], with 212 and 179 citations, respectively, are relevant for analyzing the impact of regulations and financial freedom on bank performance in the European Union. Additionally, Staub et al.'s work [39], with 167 citations, focuses on evaluating the efficiency of banks in Brazil using the DEA method, making a valuable contribution to research on emerging economies. These publications reflect key themes in banking and financial studies and continue to influence research in the field.

5. Discussion

5.1. Network Analysis of Keywords

Following the bibliometric analysis based on keyword co-occurrence networks in the Web of Science and Scopus databases, several major conclusions and trends can be identified in the research related to banking efficiency in the context of digitalization and Industry 4.0.

First of all, the terms "banking" and "efficiency" stand out for their centrality and high frequency in both network maps, which emphasizes their fundamental role in the structure of the reviewed literature. This indicates that banking efficiency is a central and well-integrated topic in banking research. The fact that these terms have a high overall link strength demonstrates that banking research consistently connects to these central themes, providing a solid theoretical foundation for further research.

The thematic distribution of clusters also highlights the diversity of current concerns in banking research. For example, the clusters in Scopus and Web of Science show a clear preoccupation with topics related to bank performance, frequently measured by quantitative methodologies such as data envelopment analysis (DEA). This technique is widely used to assess the efficiency of financial institutions, highlighting the importance of quantitative analysis and technical measures in bank performance studies.

Another important aspect is the focus on digitalization and the impact of emerging technologies on the banking sector, as evidenced in clusters such as the red one in the Scopus database, which includes terms such as "big data", "decision making", and "customer satisfaction". This reflects a clear trend towards the adoption of new technologies and an increased focus on customer experience and decision-making processes assisted by advanced data analytics. Digitalization is proving to be a catalyst in the transformation of the banking industry, facilitating both operational efficiencies and increased customer satisfaction.

Moreover, there is growing attention to sustainability and the green economy, a relatively new but growing trend, reflected in clusters that include terms such as "sustainable development" and "environmental economics". This shows how the banking sector is beginning to align itself with global sustainability requirements, actively engaging in the transition to a green economy. This mainstreaming of sustainability themes indicates an evolution of the field from traditional economic performance to the inclusion of ethical and environmental considerations in the assessment of banking efficiency.

The network structure also shows a high level of interconnectedness between different themes, suggesting a well-linked literature and significant interdependence between research topics in banking. This density of linkages indicates that the literature in banking has evolved in an integrated way, where issues of performance, technology, sustainability, and governance are addressed in a complementary and interconnected manner.

In conclusion, the keyword analysis highlights a significant shift in banking efficiency research, reflecting a transition from traditional approaches to new paradigms that include digitalization and sustainability. These results underline an evolution of the field, geared towards adapting the banking sector to today's technological and environmental requirements, which contributes to the development of a more comprehensive knowledge base and a better understanding of efficiency in banking.

5.2. Authors' Co-Citation Analysis Network

The bibliometric analysis of banking efficiency research in the Web of Science and Scopus databases provides a detailed insight into the most cited and prolific authors. In the Web of Science database, An Berger dominates the list of the most cited authors, with over 7000 citations, followed by Humphrey and Levine, with several thousand citations each. These authors are essential in informing research on bank efficiency and are frequently mentioned in the literature as theoretical and methodological reference points. Similarly, other influential authors, such as Leopold Simar and Philip Molyneux, have contributed substantially to the assessment of the performance of financial institutions, with papers consistently cited in the field.

Web of Science's co-citation network analysis identifies 21 clusters with central nodes, such as Molyneux, Matousek, and Hassan, each contributing to the delineation of distinct sub-domains. For example, Matousek and Hassan have considerable work in the study of bank competitiveness and bank risk, which are both directions of major interest in bank efficiency. Regional clusters, such as the green cluster led by Fadzlan Sufian and Kamarudin, reflect a focus on specific regions, such as Southeast Asia, showing the distinct geographic concerns within the research networks.

In terms of number of publications in Web of Science, Sufian is the most prolific author, with 56 papers, followed by Yong Tan and Mike Tsionas. These figures suggest a sustained activity and extensive contribution to knowledge in the field, with a focus on bank performance and efficiency analysis. In addition to being prolific, these papers also provide a solid base of references and methodologies routinely used in assessing bank performance.

In the Scopus database, influential authors and collaborative groups are similar but with specific nuances. For example, in Scopus, the cluster formed by Sufian, with collaborators such as Habibullah, indicates an active research network and a growing interest in the application of the data envelopment analysis (DEA) method in the study of bank efficiency. Central authors, such as Casu and Girardone, are highlighted by papers on the competitiveness and efficiency of European banks, having a major influence in applied studies.

The cluster analysis in Scopus revealed 51 distinct clusters, suggesting a greater diversification of sub-domains compared to Web of Science. For example, the cluster led by Casu and Girardone focuses on the competitiveness of European banks, while the green cluster, dominated by Sufian, mainly explores the efficiency of Asian banks. This comparative approach indicates distinct research directions, with each cluster representing a specific area of interest.

In terms of citations in Scopus, Casu and Girardone have the most citations, highlighting the importance of their contributions on bank performance and competitiveness analysis. They are followed by authors such as Sufian and Tan, who are known for their application of innovative methodologies and comparative approaches to efficiency evaluation. Also, authors at the edge of the networks, such as Kočišová and Aiello, suggest contributions on research niches without being part of central collaborative networks.

In conclusion, the analysis from both databases emphasizes that, although there is an overlap of frequently cited and prolific authors, there are also specific research directions, related to geographical regions or methodologies, that influence the structure of research networks. The co-citation networks and clusters in Web of Science and Scopus not only reflect significant collaborations between authors but also regional and methodological pri-

orities in bank efficiency research, providing insights into the evolution and diversification of the field.

5.3. Institutional Collaboration Network Analysis of Co-Authors

The bibliometric analysis of institutions contributing to banking efficiency research on the Web of Science and Scopus databases highlights some key players and significant regional differences. In Web of Science, institutions such as University Putra Malaysia and the World Bank have a central role, with many publications and citations. The World Bank, for example, stands out with an extremely high citation impact, suggesting that its studies are essential for applied research and global banking policy. In contrast, institutions such as University Putra Malaysia have a large volume of papers but a more modest citation rate, indicating a broad contribution but variable impact per paper.

In Scopus, the analysis reveals three distinct clusters, corresponding to varied networks of collaboration and influence. The green cluster, dominated by US institutions such as Auburn University and the Milken Institute, is oriented towards applied studies, often related to financial efficiency. The blue cluster, including the National Bureau of Economic Research (NBER) and the Federal Reserve Bank of Philadelphia, has a major impact due to the large number of citations, highlighting the role of these institutions in the development of economic policy and macroeconomic research.

European institutions, such as Bangor Business School and the Wharton Financial Institutions Center, play a key role in research on bank operational efficiency, particularly in the European context. They are grouped in a red cluster in the Scopus analysis, which indicates a significant influence on benchmarking studies geared towards optimizing bank performance in Europe. Bangor Business School contributes with studies focusing on the operational efficiency and competitiveness of European banks, while Wharton Financial Institutions Center provides an international and comparative perspective.

The differences between the collaborative networks in the Web of Science and Scopus databases highlight two distinct orientations. In Web of Science, the network has a global reach, with strong connectivity between institutions in Asia and Europe, reflecting extensive international collaboration. In contrast, Scopus highlights more clearly the regional and thematic structure of the academic networks: institutions are more closely linked on applied topics such as impact studies and institutional efficiency analysis, suggesting a greater interest in the practical aspects of banking efficiency. This difference in focus and collaboration between the databases indicates both distinct regional networks and varying thematic priorities in bank efficiency research.

5.4. Examination of Specialized Journals

The analysis highlights the important role of certain prestigious journals, such as the Journal of Banking and Finance, in developing and supporting research on bank efficiency. This journal is a major point of reference, and its central position and interconnection with other journals suggests that many studies use the articles published there as a theoretical and practical basis. Through its large volume of citations and links, the journal promotes conceptual continuity, helping to maintain and evolve key themes such as operational efficiency and banking performance.

At the same time, there is an interesting dynamic between traditional research and new areas of interest. Recent publications in journals such as Sustainability (Switzerland) suggest that sustainability topics are becoming increasingly relevant in the discussion of banking efficiency, reflecting an adaptation to current trends that emphasize banks' social responsibility and environmental impact. This may reflect a shift in the priorities of researchers and financial institutions as the banking sector reconsiders its strategies in a changing global economic context characterized by an increased focus on sustainability.

The analysis also highlights strong links between journals focused on applied aspects of bank efficiency, such as Applied Economics and Managerial Finance, and newer sustainability-oriented journals, suggesting an integration of financial efficiency studies

with new perspectives, bringing to the fore the impact on communities and the wider economy. This interlinking of journals with different orientations shows that the field of bank efficiency is constantly evolving, being shaped by new perspectives and approaches, such as those on financial sustainability and resilience.

In essence, the submissions highlight a dynamic academic network, where classical and emerging research meet and complement each other, strengthening theoretical foundations while responding to contemporary challenges in the banking sector.

6. Conclusions

The bibliometric analysis of banking efficiency research, based on data collected from two major databases, Web of Science and Scopus, highlights key transformations and trends in the field. The findings highlight key directions of development and the increasing relevance of modern topics, reflecting the complexity and accelerated evolution of the banking sector.

First, the central role of the concepts of banking efficiency and performance is evident from the centrality and high frequency of the terms "bank" and "efficiency" in both databases. This underlines the importance of these concepts in the literature and reveals a well-integrated and long-standing underlying concern with improving bank performance. This consistency suggests that the topic of bank efficiency provides a sound theoretical foundation for further and expanded research in this area.

Second, the diversity and complexity of the thematic clusters identified in the reviews indicate a wide range of sub-themes in bank efficiency research. Thus, there has been a particular emphasis on quantitative techniques, such as efficiency frontier analysis (DEA), used to assess the performance of financial institutions. In addition, a trend towards the integration of emerging technologies and advanced data analytics has been identified, suggesting an adaptation to new technologies that is redefining both operational efficiency and customer experience in banking.

Third, sustainability and the green economy are emerging as priorities in banking efficiency research through terms such as "sustainable development" and "environmental economics". This development reflects an alignment of the banking sector with global sustainability requirements by integrating ethical and environmental factors into the assessment of efficiency. This is redefining banking efficiency beyond traditional financial criteria to include the contribution to sustainable development objectives.

Moreover, the analysis of co-citation networks and institutional collaborations in the two databases highlights global collaborative networks as well as regional partnerships. Renowned authors and institutions—such as An Berger, World Bank, and University Putra Malaysia—have a significant influence on research directions. In the Web of Science database, collaborative networks have a global coverage between Europe and Asia, whereas Scopus emphasizes regional structure and application aspects. This differentiation between the bases suggests complementary perspectives: a global approach and a more context-dependent, applied focus.

Finally, prestigious journals, such as the Journal of Banking and Finance, play an important role in supporting and promoting conceptual continuity in the field of banking efficiency. At the same time, sustainability themes are being picked up by more recent publications, such as Sustainability (Switzerland), which reflect a growing interest in social responsibility and environmental impact in the assessment of bank performance. This integration of traditional research with modern themes illustrates a continuous evolution of the field by adapting to new economic and social challenges and demands.

Thus, the analysis of the two databases highlights a major transition in banking efficiency research from traditional approaches to modern paradigms incorporating digitalization and sustainability. These results underline the evolution of the field towards adapting to today's technological and environmental requirements, contributing to a broader knowledge base and a deeper understanding of efficiency in banking.

While the primary focus is on bank efficiency, our analysis indirectly contributes to understanding how digital strategies in banking can influence broader societal and economic outcomes, such as financial inclusion and economic upgrading, which are of great importance in the context of Industry 4.0 technologies.

Thus, the present study also extends the analysis of bank efficiency from a digitalization perspective, complementing the research of Schaeck and Cihák [91], which focuses on bank efficiency in the context of financial competition and stability. Moreover, it joins the work of Manta et al. [94], which explores the impact of Industry 4.0 on bank efficiency, bringing an additional dimension of sustainability goals. Thus, this research integrates traditional and technological perspectives, emphasizing the role of digitalization in promoting bank efficiency and contributing to urban sustainability goals.

However, the study contrasts with Chortareas et al. [92] and Barros et al. [89]. While these works focus on bank efficiency from specific regulatory and performance measurement perspectives, this study explores how bank efficiency is approached in the context of digital transformation for sustainability goals. As such, the article provides a more recent and integrated view of the impact of digital technologies on bank efficiency compared to traditional studies focused on regulation and economic performance.

Given the focus of the literature review on banking efficiency in the context of Industry 4.0, it would be beneficial for policymakers to encourage investment in digital technologies in the banking sector to increase efficiency and support sustainability objectives. The need for a "risk-oriented" approach underlines the importance of developing policies to strengthen banks' capacity to manage risk, particularly in the context of the pressures generated by digitalization and sustainability requirements.

Also, it is recommended that, in light of the research on the impact of regulation on bank efficiency, policymakers undertake a review and adjustment of existing policies with a view to achieving an optimal balance between competition, efficiency, and safety in the banking system. Additionally, policymakers should encourage international collaborations, as highlighted by the institutional analysis. This will facilitate knowledge sharing and support the development of effective practices in the banking sector, as well as encourage partnerships between financial institutions, universities, and global organizations.

The limitations of this study include the dependence on the selected database and paper selection criteria, which may exclude relevant studies. Future research directions could include exploring the impact of new financial technologies on bank efficiency, benchmarking bank efficiency across geographical regions and investigating the role of corporate governance in optimizing bank performance. It is recommended that future research should further explore AI, green finance, and digital affordability in order to strengthen the relationship between banking efficiency and sustainable cities. Further studies on the sustainability and environmental impact of banking practices, considering current trends and the future of the banking sector, would also be useful.

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