

Artificial Intelligence in Financial Risk Early Warning Systems: A Bibliometric and Thematic Analysis of Emerging Trends and Insights

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Abstract—With the continuous development of financial markets worldwide, there has been increasing recognition of the importance of financial risk management. To mitigate financial risk, financial risk early warning serves as a risk uncovering mechanism enabling companies to anticipate and counter potential disruptions. The present review paper aims to identify the bibliometric analysis for exploring the growth and academic evolution of financial risk, financial risk management, and financial risk early warning concepts. Academic literature is surveyed from the Scopus database during the period 2010-2024. The network analysis, conceptual structure, and bibliographic analysis of the selected articles are employed using VOSviewer and Bibliometric R Package. The biblioshiny technique based on the bibliometric R package was used to draw journal papers' performance and scientific contributions by displaying distinctive features from the bibliometric method used in prior studies. The data was extracted from Scopus databases. In addition, this study comprehensively analyzes the evolution of financial risk early warning systems, highlighting significant trends and future directions. Thematic evaluation across 2010-2015, 2016-2021, and 2022-2024 reveals a shift from traditional statistical methods to advanced machine learning and AI techniques, with neural networks, random forests, and XGBoost being pivotal. Innovations like attention mechanisms and LSTM models improve prediction accuracy. The integration of sustainability factors, such as carbon neutrality and renewable energy, reflects a trend towards incorporating environmental considerations into risk management. The study underscores the need for interdisciplinary collaborations and advanced data analytics for comprehensive financial systems. Policy implications include promoting AI adoption, integrating environmental factors, fostering collaborations, and developing advanced data analytics frameworks.

Keywords—Artificial intelligence; deep learning; financial risk management; early warning systems; bibliometrics analysis

I. INTRODUCTION

In the dynamic landscape, the financial risk of companies is an unavoidable risk and inevitable companion which is reflected in all parts of company investment and financing management. The presence of financial risks presents a huge vulnerability to the healthy advancement of companies [24]. In an era of volatility, uncertainty, complexity, and ambiguity firms have been subjected to unprecedented exposure, which complicates decision-making [1]. In the current era of the Internet plus, the world economy is becoming more and more

globalized and informational. The business environment is changing rapidly, and the business development of enterprises is facing unprecedented opportunities for their operation and development. However, it is also facing financial uncertainties brought about by the fluctuations of the general economic environment, and the company is facing increasing financial risks. It also faces unpredictable environmental factors and challenges such as economic market factors, laws and regulations, social and cultural factors, and policy environment factors which bring uncertainty to the financial situation of enterprises, and the financial risks faced by enterprises are also increasing.

The role of the financial market in enabling societies to reach the low carbon economy is well understood [26]. The market competition has become rigorous under the influence of "economic globalization" and enterprises are under pressure for both survival and growth. Low-carbon development has greatly changed the external environment and financial environment of enterprises, thereby increasing the financial risks that exist in enterprises. In the context of financial development globalization, financial market transactions between countries are frequent, the financial environment is more complex, and the spread of financial risks is more rapid and extensive. Especially, in the current international financial situation with high leverage, high asset prices, high market volatility, and high risk, financial supervision will become more difficult, and the possibility of a financial crisis outbreak is higher than before. A financial crisis will not only destroy a country's financial system and international financial order but also cause great damage to the real economy, causing an economic crisis, and even causing a serious social and political crisis, endangering national security.

Financial risk exists in the management process of an enterprise, and poor management or poor decision-making can cause the level of financial risk to exceed alarming values and lead to financial crisis [24]. The reason why most enterprises encounter a serious financial crisis or even close in the later stage is that they do not pay full attention to the initial financial problems and do not take effective measures to deal with the crisis in time. Therefore, it is very practical to establish a scientific data model to analyze and forecast the financial data of enterprises. It can not only monitor the financial situation of enterprises in real time but also play an

effective role in financial early warning [22]. Financial risk warning has become an important part of modern enterprise financial management. It helps enterprises better warn, prevent, and control financial risks which can reduce the loss and increase the profit. In recent years, there has been worldwide research on the issue of financial risk in developing countries, particularly from the perspective of a low-carbon economy it has become a hot issue.

Detailed literature is scarce on financial early warning predictions for the financial risk of enterprises. Recently, [19] documented that bibliometric analysis has been prominently conducted for the literature on topics including sustainable and Islamic finance [31], credit risk [33], financial crises, and efficiency measurement [10]. However, other topics, such as liquidity risk or ownership structure, have been comparatively neglected. Furthermore, based on our extensive review and study, it has been found that researcher focused on early warning systems in business, finance, and economics, and [44] have worked on risk management. In addition, much empirical research has been conducted on financial risk for enterprises, banks, and currency crises. However, a lack of evidence has been found that focuses on bibliometric analysis of financial risk early warning systems. Therefore, the goal of this study is to explore the recent progress, challenges, and future directions of financial early warning predictions to capture the significance of financial early warning predictions and linked areas through bibliometric and thematic analysis. Despite the growing importance of financial risk early warning systems, there remains a significant research gap in comprehensive bibliometric and thematic analyses that leverage updated data from the Scopus database. Previous studies have not fully utilized these methods to map the evolution and emerging trends in this field, particularly over the extended period from 2010 to 2024. This study addresses this gap by employing a robust bibliometric and thematic analysis, offering a novel perspective on the financial risk early warning landscape. By systematically categorizing themes into high occurrence and link strength keywords, emerging topics, niche areas, interdisciplinary and technological integration, and sustainability and innovation, this research provides a detailed and updated overview of the current state and future directions of financial risk management. This study's findings hold significant implications for policymakers. The identification of cutting-edge technologies such as neural networks, random forests, and XGBoost, as well as emerging areas like attention mechanisms LSTM, and GRU models, underscores the need for advanced analytical tools in financial risk prediction. Furthermore, it focuses on sustainability and consolidation of environmental factors into risk management which signifies the growing connectivity of financial stability and environmental responsibility. By providing a comprehensive overview of current and future trends, this study equips policymakers with the insights necessary to foster innovation and sustainability in financial risk management, ultimately contributing to more resilient and adaptable financial systems.

Our main objectives of the study are as follows:

- 1) To examine the historical distribution of financial risk early warning system articles, illustrating contributions through metrics such as average citation per year, core sources by Bradford's Law, most cited

countries, corresponding author's countries, and most relevant sources.

- 2) To identify prevalent research themes in financial risk management, highlight potential collaborations and interdisciplinary research opportunities, and suggest venues for future research to advance the field.
- 3) To offer policy recommendations to enhance the adoption of advanced AI techniques and sustainability considerations in financial risk management, encourage interdisciplinary collaborations and the development of advanced data analytics frameworks, and outline future research directions to address gaps and build on the study's findings.

A. Methods

The method used in this study is bibliometric analysis, which was first used by [34] and is popular among the researchers in supporting quantitative analysis in understanding the literature. The word bibliometric is the statistical analysis of scholarly communication through publications and the most common methods are variants of citation analysis. Bibliometric analysis is usually a machine-like mechanism to understand the research trends globally in an area of interest based on the output of academic database literature and is different from a typical review paper focusing on recent progress and challenges and future directions for a specific topic [20]. Bibliometric is a powerful tool for the management of information providing useful analytical results across many fields and its application in finance are relatively recent [25], [42].

B. Search Strategy and Sources of Data

According to [15] Scopus, Web of Science, and Google Scholar are the three main databases for academic literature and citation indexes. However, this study chooses the Scopus database because Scopus is the largest citation and abstract database covering a wide range of subjects and thus, this is an attempt to cover more topics, that might not be available with the Web of Science database. Google Scholar is not selected because it does not have a strong quality control process [13]. The first search on the Scopus database was conducted on 5 October 2023 with a central theme of "enterprise financial risk" in the title, abstract, and keywords resulting in 112 documents. Moreover, subsequent searches were made between October 2023 and December 2023, on a trial-and-error basis to check for any different results, issues, and shortcomings with the Scopus Database. The authors use the same central theme along with enterprise financial management and various other variants like financial risk prediction, corporate financial information risk, crisis assessment, and credit risk management, and the authors got different results. This change in the result at a different time was the same when other variants in the search string were used. Following this, the author used different search strings which finally led to the result of 150 documents by restricting it to journal articles only as these are most used to present academic novelties [13].

The subsequent keywords were explored simultaneously with a central theme as: with a central theme as "enterprise financial risk" OR "early warning system" and its related concept in the title level of the search tool which resulted in 150 documents. These comprehensive search strings were

selected because they are highly associated with the topic of interest in this study to cover the relevant body of literature. Thus, the final query string used is as follows: TITLE-ABS-KEY (“enterprise financial risk” OR “enterprise financial management” OR “enterprise financial information management” OR “financial risk” OR “financial risk prediction” OR “financial risk analysis” OR “financial risk assessment” OR “Financial management risk prediction” OR “financial crisis management” OR “corporate financial information risk” OR “corporate financial information risk management” OR “crisis assessment” OR “credit risk management”) AND (“Early warning system*” OR “ews*” OR “Financial early warning system*” OR “financial early warning model” OR “Financial risk warning” OR “financial risk prediction” OR “financial risk prediction model” OR “Risk prediction” OR “financial analysis system*”) AND (“neural network*” OR “deep learning”) AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (SRCTYPE, “j”)) AND (LIMIT-TO (PUBSTAGE, “final”)) AND (LIMIT-TO (OA, “all”)).

For selecting and screening the article, the authors used guidelines by “preferred reporting items for systematic reviews and meta-analyses” (PRISMA) for systematic research reviews as shown in Fig. 1. While screening, the eligibility and inclusion criteria the authors could ensure that no potential review article skips the Scopus Database filter. To check and ensure that there are no review articles, or any other potential irrelevant articles present in our analysis that might not have skipped our filtration process. Therefore, additional phrases such as bibliometric review, scientometric review, systematic literature review, systematic review, meta-analysis, science mapping, development, progress, recent, revisit, trends, prospects, advance, perspectives, reviews, and so on, as mentioned in [20] were used using conditional formatting toolbar in MS Excel and noted the documents Electronic Identifications (EIDs). Moreover, these articles were examined by reading the title and abstract, and if needed, the articles were read thoroughly to make sure that the articles were related to enterprise financial risk and financial risk warning. There are no missing authors’ names and IDs, and no articles were found to be duplicated.

C. Bibliometric Analysis Using VOSviewer

The study used VOSviewer (version 1.6.18) developed by the Centre for Science and Technology Studies, Leiden University, Leiden, Netherlands, to visualize the financial risk warning system and its related concepts in the number of articles, prolific authors, and most productive journals in maps. The descriptive analysis shows the configuration of many articles, types of articles, and articles over time of the Scopus Database, while the bibliometric analysis is performed using the co-authorship and co-occurrence analysis. Fig. 2 depicts the methodology for bibliometric analysis using VOSviewer. Information regarding the final 150 documents like bibliographical information, citations, and keywords were exported to VOSviewer’s latest version. The authors used VOSviewer because our main objective is to focus on an aggregate level and over time development of a research area [13]. VOSviewer is a tool for creating and displaying bibliometric maps using items. In this study, the objects of interest like author keywords and countries are the items. There can be a connection, relation, or link between each pair of items. Each connection

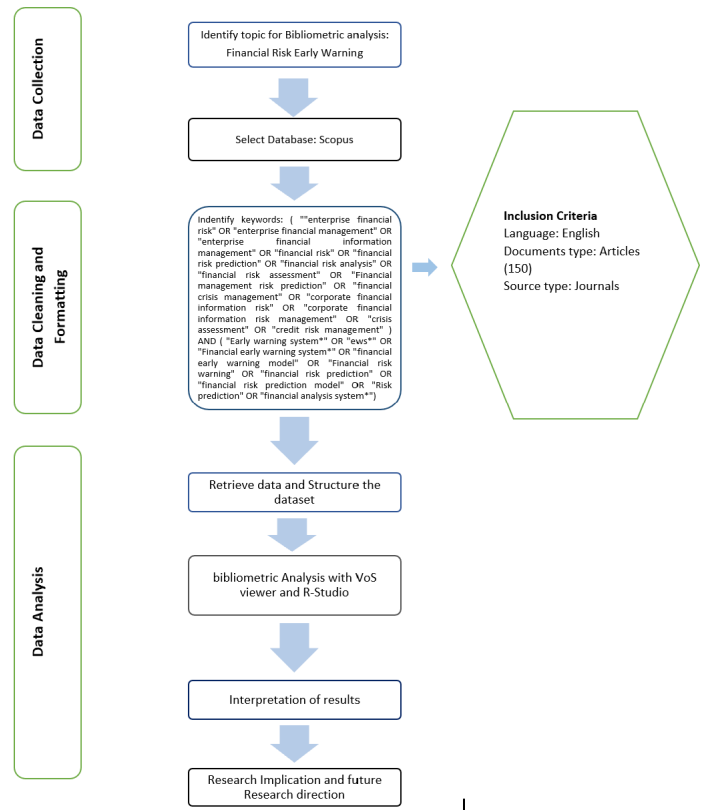


Fig. 1. Research process adopted in the study. Author’s compilation.

or link has a strength, which is represented by a positive numerical value, and the higher the value is, the stronger the link between the two linked items becomes. In the case of co-authorship analysis, the link strength between the countries shows the number of publications that two affiliated countries have co-authored. Meanwhile, the co-authorship links the total strength of a given country to other countries. In the case of co-occurrence analysis, the link strength between author keywords shows the number of publications in which two keywords occur together.

1) *Co-authorship Analysis*: In scientific research, co-authorship is the most formal manifestation of intellectual cooperation. It entails collaborating with two or more authors in conducting a research study, resulting in a higher quality or quantity research output than could be achieved by a single author [16]. Co-authorship research can be done at the organization and country level because bibliographic data contains details about the authors’ institutional affiliations and geographic positions. In this analysis of co-authorship, the unit of analysis chosen is country; therefore, the authors have included all the countries affiliated with many authors. The international research collaboration domain is under the influence of bibliometric research analysis and its main methodology is co-authorship analysis [9]. This study considered 21 affiliated countries and the affiliated countries were clustered into seven regions: South Asia (Region 1), Africa (Region 2), East Asia, and the Pacific (Region 3), Europe and Central Asia (Region 4), Latin America and the Caribbean (Region 5), Middle East and North Africa (Region 6), and North America (Region 7).

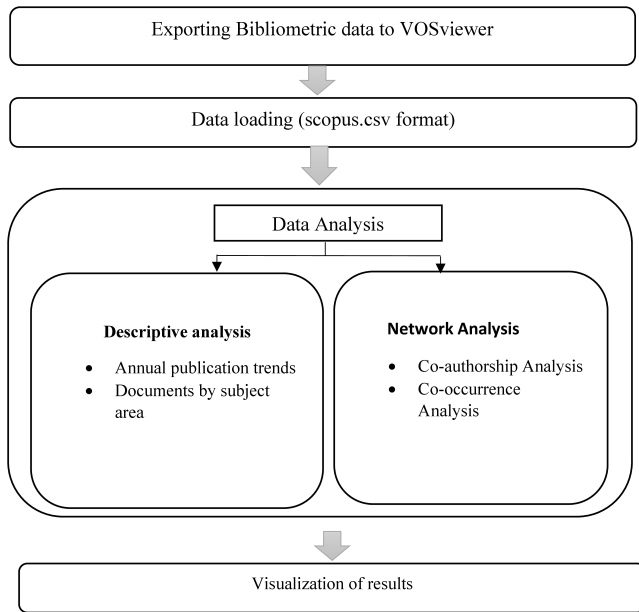


Fig. 2. Methodology for bibliometric analysis using VOSviewer.

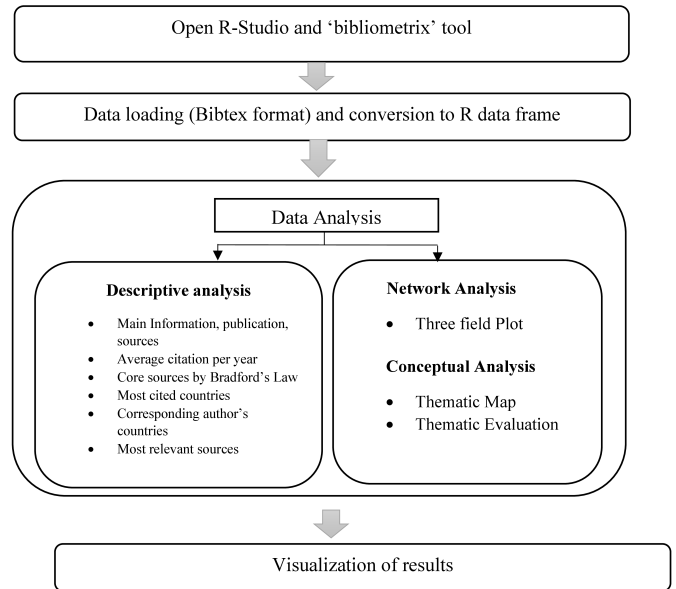


Fig. 3. Methodology for bibliometric analysis using "Bibliometrix".

2) *Co-occurrence Analysis*: Co-occurrence analyses can be used to analyze the connections of author keywords used to make a conceptual structure of the study. Researchers create a complex network using keywords because actors combine and link the words to make an interesting funnel and aggregate. Co-occurrence analysis is the only technique that uses the contents or keywords of the document to find associations among the documents. At the same time, the other approaches link the document indirectly by co-authorship or through citation [11]. Likewise, co-authorship, the association among keywords used by research studies, is represented by the strength of the keywords used in the publications in the case of co-occurrence analysis. This technique can be used that utilize the contents of the publications to make a similarity measure among documents. However, the other methods connect documents indirectly through citations and co-authorship analysis [11]. Before transferring to VOSviewer, synonymous terms were identified and replaced with a single term. The study sets a minimum limit of keyword linkage to 2 in co-occurrence in VOSviewer. Overlay visualization is considered to explore the keywords' yearly publications, occurrences, and connections.

D. Bibliometric Analysis Using Bibliometrix

As the number of published research continues to grow at an increasingly rapid rate, the effort required to accumulate knowledge becomes more complex. "Bibliometrix" is a tool programmed in the R platform (<https://www.bibliometrix.org>) to perform a comprehensive bibliometric analysis of published literature. There are several packages in R dealing with bibliometrix; however, none of them address the entire workflow process [4]. The procedure for performing bibliometric analysis using "Bibliometrix" is shown in Fig. 3.

II. DISCUSSION

A. Data Analysis and Bibliometric Maps

Table I provides a comprehensive summary of the main information, publications, and sources regarding the articles selected from the Scopus database for the bibliometric analysis of financial risk early warning from 2010 to 2024. The dataset encompasses a total of 77 sources, which include various journals, books, and other publications, amounting to 150 documents. Despite the consistent number of documents each year, the annual growth rate remains at 0%, indicating no year-over-year increase in publications. On average, these documents are relatively recent, with an average age of 2.07 years, and each document has been cited approximately 5.96 times. Interestingly, no references were reported in this summary.

The content of these documents includes 929 instances of Keywords Plus, which are terms frequently appearing in the titles of an article's references and are used to enhance the author's keywords. The authors provided a total of 291 unique keywords. The analysis reveals that 335 authors contributed to these documents, with 33 of them authoring single-authored papers. On average, each document had 2.71 co-authors, and 17.45% of these documents featured international co-authorship, highlighting the global collaboration in this research area. The types of documents varied, with the majority being articles (129), followed by conference papers (13), reviews (4), book chapters (2), and retracted papers (2). Table I summarizes the key information of the articles selected from the Scopus database using the "bibliometrix" tool.

Fig. 4 illustrates the annual trend in the number of articles published on the topic of financial risk early warning from 2010 to 2024. The x-axis represents the years from 2010 to 2024, while the left y-axis shows the number of seed index articles published each year and the right y-axis depicts the cumulative number of these articles. The bar chart represents the yearly publication count, and the line graph indicates the

TABLE I. SUMMARY OF THE SELECTED ARTICLES FROM SCOPUS DATABASE

Description	Results
Time-span	2010:2024
Sources (Journals, Books, etc)	77
Documents	150
Document Average Age	2.07
Average citations per doc	5.96
DOCUMENT CONTENTS	
Keywords Plus (ID)	929
Author's Keywords (DE)	291
AUTHORS	
Authors	335
Authors of single-authored docs	33
AUTHORS COLLABORATION	
Single-authored docs	33
Co-Authors per Doc	2.71
International co-authorship %	17.45
DOCUMENT TYPES	
article	129
book chapter	2
conference paper	13
retracted	2
review	4

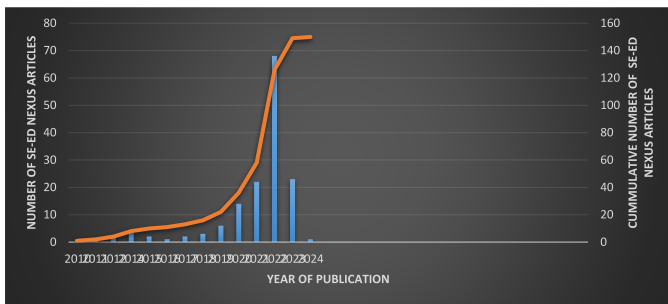


Fig. 4. Annual trend of financial risk early warning (2010-2024) Source: Scopus Database.

cumulative total. The data reveals a clear upward trend, particularly from around 2019 onward, highlighting a significant increase in publications related to financial risk early warning during this period.

Fig. 5 presents a pie chart categorizing the selected documents by their subject area, offering a visual overview of the distribution of topics. The chart shows that the majority of documents fall within the Social Sciences (19.3%), followed closely by Business, Management, and Accounting (16.8%), and Economics, Econometrics, and Finance (15.7%). Environmental Science accounts for 14.3% of the documents, while Energy comprises 11.0%. Other fields are represented to a lesser extent, including Engineering (5.9%), Computer Science (4.0%), Arts and Humanities (3.3%), Decision Sciences (2.1%), and Mathematics (2.0%). The remaining 5.5% of documents are categorized under “Other”, indicating a diverse range of additional subject areas.

Fig. 6 illustrates the average number of citations per year for publications related to financial risk early warning systems. It helps in understanding the impact and relevance of research over time. A higher average citation per year indicates that the work is widely recognized and used by other researchers in the field. In Fig. 7, Bradford’s Law describes the distribution of articles on a particular subject in scientific journals. This figure shows the core journals that publish the

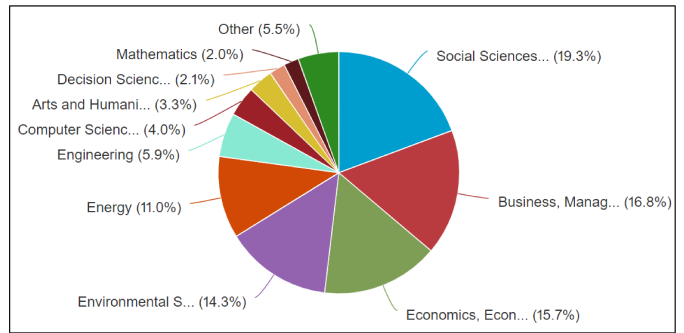


Fig. 5. Documents by subject area.

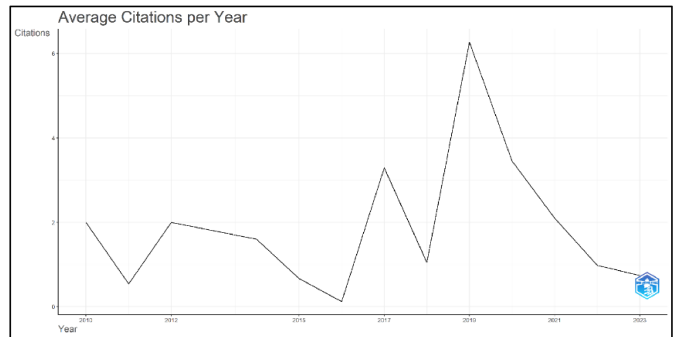


Fig. 6. Average citation per year.

most significant number of articles on financial risk early warning systems. It helps in identifying the key sources and journals that contribute extensively to the research in this domain. Fig. 8 highlights the countries whose research on financial risk early warning systems has received the most citations. It shows the geographical distribution of influential research and indicates which countries are leading in this field. Fig. 9 represents the countries of the corresponding authors of the publications. It provides insight into the geographical distribution of researchers who are contributing to the literature on financial risk early warning systems. Fig. 10 lists the most relevant sources or journals that publish articles on financial risk early warning systems. It helps researchers identify the best sources for publishing their work and staying updated with the latest research.

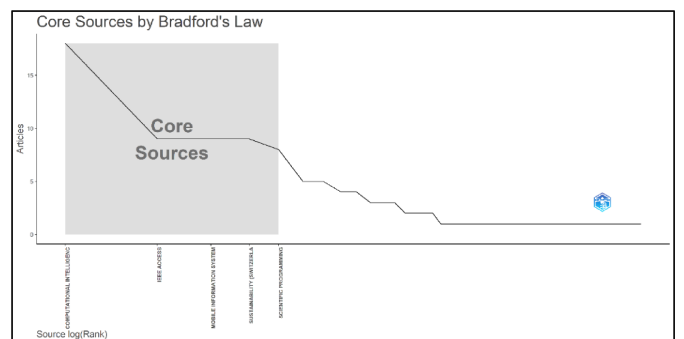


Fig. 7. Core sources by Bradford's law.

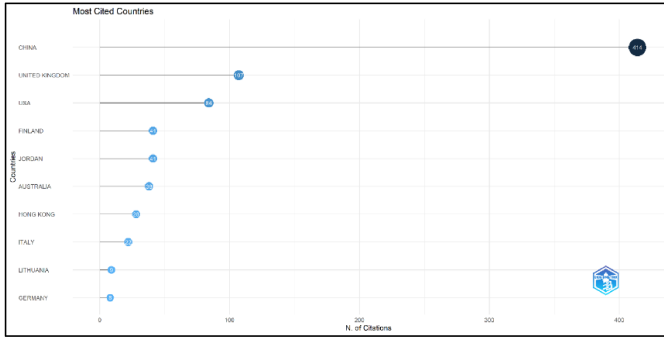


Fig. 8. Most cited countries.

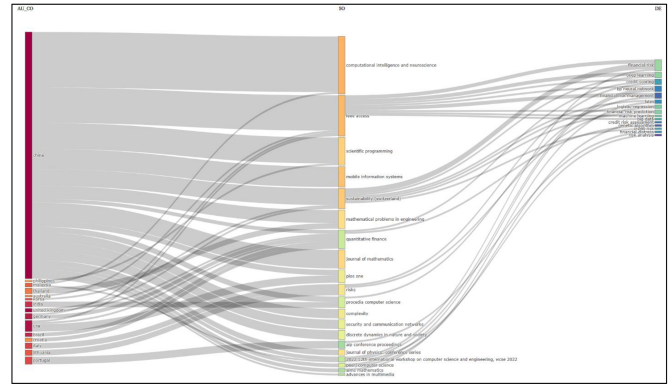


Fig. 11. Three fields plot of country-journal-keyword.

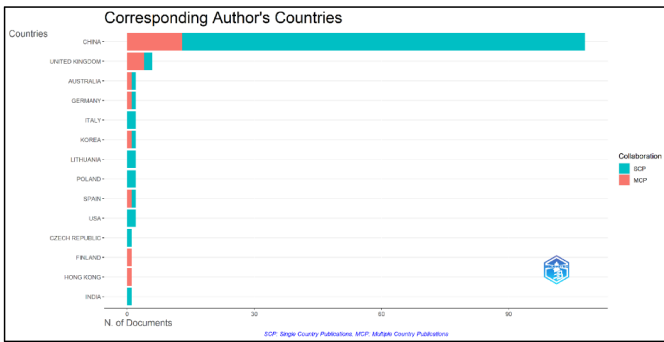


Fig. 9. Corresponding author's countries.

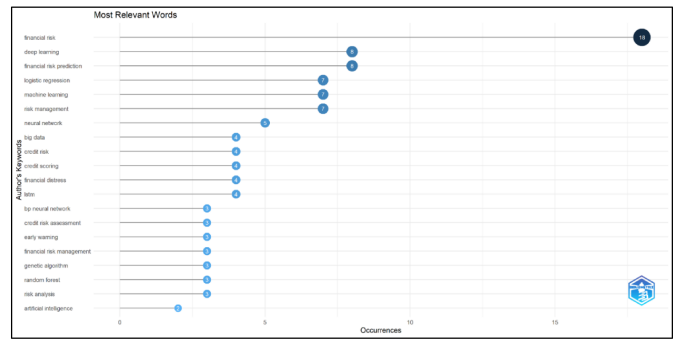


Fig. 12. Most related keywords.

Fig. 11 visually represents the relationship between countries, journals, and keywords in publications related to financial risk early warning systems. It shows how different countries and journals are linked through common research themes and keywords, providing a comprehensive overview of the research landscape.

Fig. 12 titled “Most Relevant Words” displays the occurrences of various keywords related to financial risk early warning systems. The Keywords such as “financial risk”, has the highest frequency of occurrence which is 8 times, followed by “deep learning,” and “financial risk prediction”. It reflects the critical significance and recent research progress of these keywords. Terms like “logistic regression”, “machine learning”, and “risk management” appear with 7 occurrences

which supports the fact that these statistical and analytical tools are commonly used in the existing financial risk studies. The keyword “neural network” has been used 7 times which portrays the fact that it is widely used in modeling and prediction of financial risks. The terms “big data”, “credit risk”, “credit scoring”, “financial distress”, and “LSTM” occurs four times which underlines the importance of advanced data techniques and specific risk factors reviewed in the existing body of literature. The key terms of “BP neural network”, “financial risk management”, “credit risk assessment”, “early warning”, “random forest”, “risk analysis”, and “genetic algorithm” were repeated 3 times which revealed acute nature and special approaches and focus areas within the general subject. Lastly, “artificial intelligence” appears with 2 occurrences emphasizing the growing role of AI in financial risk mitigation. All the keywords are supported by the studies of [32] on deep learning applications which reflects the current research focus in the emerging area of financial risk early warning systems.

B. Co-authorship Analysis

Fig. 13 uses various colors to represent the distribution of countries across seven regions. The thickness of the lines indicates the strength of connections between countries, with thinner lines denoting weaker links and thicker lines denoting stronger ones. For instance, Cluster 3, which represents East Asia and the Pacific, includes nine countries, while Cluster 4, representing Europe and Central Asia, includes eight countries. Clusters 1, 2, 5, and 7 each include one country, and Cluster 6 (Middle East and North Africa) does not include any country

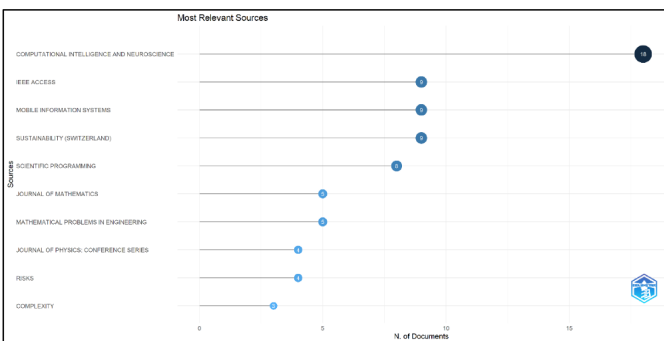


Fig. 10. Most relevant sources.

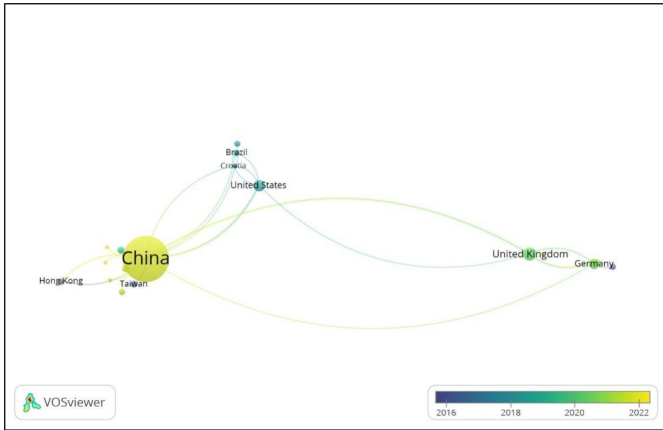


Fig. 13. Screenshot of bibliometric map based on co-authorship with overlay visualization. (It can be opened through <https://bit.ly/41uMpVT>).

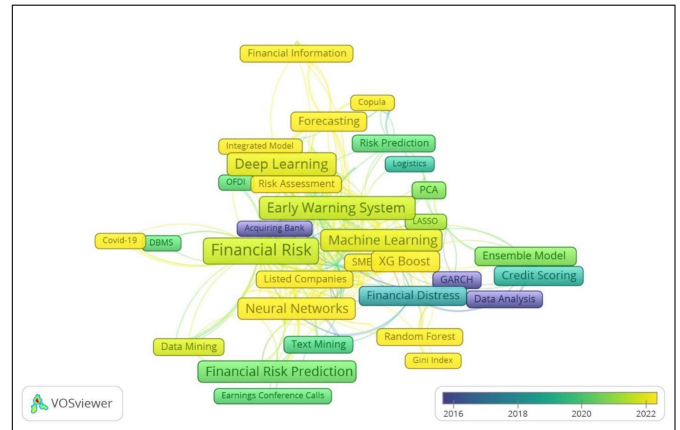


Fig. 14. Bibliometric map based on Co-authorship with overlay visualization. (It can be opened through the URL in VOSviewer: <https://bit.ly/3NCzewu>).

working in this area. Our co-authorship statistics show that China has the highest degree of affiliation, with 15 links and a link strength of 24. This means China is linked to 15 territories or countries with 24 instances of co-authorship. The United Kingdom follows with six links and a link strength of nine, the United States with five links and a link strength of eight, Germany with five links and a link strength of seven, Brazil with five links and a link strength of five, and Hong Kong with two links and a link strength of three. Other countries have fewer than two links. International collaboration occurs for various reasons, including the subject matter, the type of issue, and the researchers chosen to work on it. Additionally, the ease of access to primary data, such as financial risk early warning, can influence the relevance of the region to funders who support the research, research partners, diversity, and collaboration.

C. Author Keywords and Current Emerging and Future Trends Regarding Financial Risk Early Warning System

This section represents the objective, which explains the current trends and arena for further research and potential collaboration using VOSviewer software. For mapping in VOSviewer, a total of 291 keywords were recorded and after re-labeling various variants or synonymic single words and phrases, 177 keywords met the threshold of a minimum of five occurrences. Our results portray that financial risk is the most reflected keyword with 20 occurrences, 55 links to other keywords, and a total link strength of 74 followed by financial risk management (11 occurrences, 34 links, 47 link strength), and early warning system (11 occurrences, 29 links, 37 link strength). Some other methodological terms include deep learning (11 occurrences, 26 links, 37 link strength), logistic regression (9 occurrences, 36 links, 42 link strength), machine learning (8 occurrences, 28 links, 37 link strength), and Bp neural network (7 occurrences, 22 links, 25 link strength). Financial risk and financial risk management and early warning systems are also seen to be co-occurring with each other. whereas the early warning system keywords have links with other new emerging keywords i.e. low carbon economy, financial stability, internet finance, and internet of things. This bibliometric image shows that the two big bubbles

financial risk and financial risk management are areas used with common areas like financial distress machine learning, Xg boost, logistic regression, Bp neural network, clustering, deep learning, and nearest neighbors (Fig. 14).

The analysis of the keywords of the current articles allows for identifying the emerging trends in the research field [13]. The recent average year of publications represents potential hotspots for the future, and the smaller number of occurrences indicates the niche area [20]. Thus, Table II offers an in-depth analysis of author keywords and future trends in the realm of financial risk early warning systems. The table lists keywords alongside their occurrences, total link strength, and average publication year, thereby elucidating the current research focus areas and emerging topics within this field. Table II keywords are categorized as high occurrence and link strength keywords, emerging topics and niche areas, integration of non-related fields and technologies, sustainability and creativity, and other important keywords.

1) *High Occurrence and Link Strength Keywords:* The following keywords occur frequently and their link strength in conducting studies on the financial risk early warning system underscores the crucial role of employing machine learning and deep learning approaches in this area. Neural networks are one of the most important areas of research, being mentioned 9 times, having a link strength of 34, and the average publication year 2022. This approach enables us to train models with high levels of complexity, capable of identifying intricate patterns in the financial data, thus improving predictive performance. This is evident from [32], [41] who showed how neural networks can be applied to analyze large volumes of data by learning from huge data sets and adapting to new models of risks in the financial markets. Further, random forests occur 3 times with 13 link strengths and an average year of publication in 2022, 33, highlighting its importance. Random forests are highly valued due to their ability to handle diverse, large, and even noisy data sets in financial applications. Random forests, which construct multiple decision trees and combine their outputs, can give accurate risk estimates and overcome overfitting. The [5] further stated that there are several benefits of random forests, especially in financial risk management, mainly because of their ability to manage big data and many

variables which makes them very popular among practitioners. The term XGBoost stands out as a prominent approach that has the most link strength of 32 and is used 7 times with an average publication year in 2022 is 57. It is popular due to its ability to handle big data and is considered one of the best algorithms for predictive analysis. It also employs gradient-boosting techniques in the improvement of the predicted results and improves model accuracy. Research by [14] demonstrated that by employing the iterative nature of the XGBoost approach, additional improvements can be achieved to improve model predictive capabilities, which makes it valuable in the field of developing early warning systems for financial risks. Based on these keywords, it is shown that machine learning plays a crucial role in improving the capabilities of early warning systems for potential financial risks. Through the integration of the advantages of neural networks, random forests, and XGBoost, it is possible to improve the accuracy of these models and achieve better prediction of capacities in the financial risks that can help in the development of resilient financial systems that might be more sustainable.

2) *Emerging Topics:* Emerging themes that stand out in the field of financial risk early warning system research are the keywords “Attention Mechanism” and “LSTM (Long Short-Term Memory)” which represent the cutting-edge approaches and trends in the field. Even though the attention mechanism only emerged twice, it has a rather large link strength 8 and, the average year of the publication is 2023. This indicates that it is gradually becoming more relevant since it aims at increasing the explainability and reliability of financial risk models. The use of attention mechanisms gives the model the ability to adjust the relevance of the input features, thus resulting in better classification. LSTM is the most recurrent term with 5 references and a link strength of 17; it is mostly used in articles published in the year 2022 80, implying that this activity has become increasingly essential in recent years. Hence, LSTM models are highly effective in capturing temporal dependencies of financial data and are especially useful in determining temporal characteristics of financial data sets where past trends can influence future outcomes. Their ability to retain information over long sequences assists in capturing the temporal dependencies inherent in financial data, which are useful in improving the output of risk estimation [38]. Therefore, these topics demonstrate that innovative solutions continue to be introduced to increase the capabilities of early warning systems for financial risk management.

3) *Niche Areas:* Niche areas of concern in the financial risk early warning system are keywords like green credit risk, conditional quantiles, and sliding window, which are concerned with specific and emerging facets of financial risk management. Green credit risk features industry-specific credit risk evaluation that considers ecological aspects. This keyword emphasizes the need to come up with sector-specific solutions to managing risk that is associated with environmental sustainability. Given that many industries and financial institutions are now aware of the effect of environmental factors on financial stability, it becomes apparent that it is pertinent to work on the integration of green credit risk with these factors. In their article, [45] explain how integrating environmental factors into reporting processes that involve evaluations of risk, mitigation, and impact can provide a wider and truer perspective of the potential dangers and consequences of certain actions

by identifying carbon footprints, investing in renewable, and incorporating sustainability measures. This niche area is of great importance for the development of financial solutions that make it possible not only to mitigate various risks but also to achieve organizational growth in terms of sustainable development; the thought refers to the ecological aspect of financial risk management.

Conditional quantiles with 1 paper and a link strength of 4 and sliding window as another topic with 1 paper and a link strength of 4 published around 2023 also present emerging niche areas, which highlight that modern academic research in the field is focused on more sophisticated statistical methods to learn refined financial risks models. On the other hand, conditional quantiles focus on the probability distribution of the financial data so that business organizations can determine the likelihood of a particular risk, offering a better solution than simple quantiles regarding probable risks. This approach provides a better assessment of risk considering all the probabilities rather than risk means or medians [29].

Collectively, these niche areas highlighted that there is an immense focus on improved and specific innovations in the management of financial risk. Some of them underscore the significance of sector-based risk analysis and the application of state-of-the-art techniques in statistics to enhance the predictive capabilities of financial risks. These approaches contribute to a more resilient financial structure due to its ability to handle challenges in the current unprecedented complex financial world.

4) *Interdisciplinary and Technological Integration:* The keywords such as industry-academia linkages and public-private partnerships demonstrate that interdisciplinary and technological integration in financial risk early warning systems involves synthesizing various approaches and the use of complex analytical tools. Industry academia linkages and the use of public-private partnerships reflect the growing trend of interdisciplinary in the study of financial risk. Although these keywords are infrequent, with link strengths of 4 and an average year of publication around the year 2022, they highlight the need to integrate knowledge from various sectors to solve multifaceted financial risks.

In [6], the researchers demonstrate how these linkages and partnerships enable the exchange of knowledge, resources, and innovations between the academy, businesses, and government agencies. They may contribute to the generation of better management solutions to the risk factors that are associated with organizations. Through such arrangements, it is possible to solve complex financial risks that could be managed only with multiple companies’ resources, thus enhancing the comprehensiveness of managing the financial sector’s stability.

5) *Sustainability and Innovation:* Sustainability and Innovation in managing financial risks are emerging and reflected in keywords such as Carbon Neutrality Renewable Energy and Green Technology innovation. These terms suggest that there is an advancement towards the enhancement of sustainable practices together with the adoption of technologies for the enhancement of sustainable financial systems.

The keywords of Carbon Neutrality and Renewable Energy with average publication years of about 2022-2023 and moderate link strength underline the growing focus on environ-

mental sustainability within financial risk management. The [41] documented that the banking sectors and industries are gradually integrating environmental factors into the evaluation of risks. This transformation is due to increasing awareness of the financial implications of climate change and sustainability-related concerns. Integrating carbon neutrality and renewable energy into the financial risk analysis, the goal is to minimize future threats linked with detrimental environmental impacts and shift in legislation. This proactive approach assists in managing the identified financial risks more effectively, while thereby promoting more sustainable financial practices and, consequently, the development of a stronger financial system in line with global goals.

Green Technology Innovation has an average year of publication in 2023 that supports the importance of adopting new technologies in managing financial risks. The authors highlight that adopting green technologies can greatly diminish the negative effects on the environment and improve the sustainability of the systems used in finance. The application of such technologies is essential in creating new forms of innovative, better, and sustainable financial products and services. Green technology development enables moving to a green energy base, utilizing energy-saving technologies, and lowering CO_2 intensity. These advancements are critical in managing risks that are infectious in the financial systems including regulatory shocks, resource depletion, and climate changes.

Together, these keywords highlighted a paradigm shift regarding financial risk management and the incorporation of sustainability and innovation in it. Carbon neutrality and renewable energy demonstrate the progressive inclusion of environmental factors in risk management and addressing current and future risks. Green technology innovation refers to the use of innovative technologies for the improvement of sustainable innovative financial systems. By focusing on these areas, the financial industry not only seeks to minimize risks related to the environment; it also strives to grasp the opportunities in the future green economy. Thus, the combination of the strategy of sustainability with a focus on innovation provides financial institutions with the ability to be prepared for the current challenges in financial risk management and contribute to sustainable development at the same time.

6) *Additional Important Keywords:* The keyword COVID-19 is identified as occurring only once; however, it possesses a link strength of 4 and has an average publication year of 2023, which underscores the massive impact of the pandemic on various financial systems around the globe. The COVID-19 pandemic has posed several unprecedented developments in the financial market and has challenged the stability of financial institutions. The [21] presented that due to the COVID-19 pandemic, organizational economic losses, and other crises that occurred throughout the world, risk management has become an essential component for organizations to manage and ensure that they will not be affected negatively in the future. The dynamics of the financial environment especially in the money markets have been dynamically changing and the financial sector has been forced to respond to changes such as fluctuating volatilities, liquidity risks, and credit risks. The usage of this keyword in financial risk research also means that scholars are constantly evaluating the impact of the pandemic on the financial sector to capture the long-term effects and

the necessity of developing strategies that could be applied to financial shocks in the future.

Moreover, renewable energy with an occurrence of 1 time and a link strength of 3, published around 2022, declares the further linkage of financial risk management with environmental aspects. In [39], authors firmly stresses that the paradigm shift towards the use of renewable energy sources is not only one of the distinctive challenges that the world must address to mitigate climate change effects but also a factor that poses great risks in the financial sphere. This paper aims to look at the new opportunities and threats for funding green projects including wind, solar, and other renewable energy projects for banking organizations. These projects usually call for substantial upfront investments and many projects are legally and economically risky, but at the same time, they bring numerous advantages that can be considered in the long term, such as decreased operational expenses and compliance with sustainability objectives. The attention towards renewable energy for the study of financial risk has become more significant as the world focuses on the possibilities to minimize the financial risks of a more sustainable energy infrastructure.

The keyword of financial stability appears with 1 occurrence, its link strength is 4, and it was published in 2023, illustrating that the authors and researchers are equally fascinated by sustaining stability in the financial systems irrespective of several economic transformations. The [28] mention that maintaining financial sustainability remains one of the key goals for policymakers, regulators, and financial institutions, especially in an unstable economy or during the crisis's circumstances. Financial stability can be regarded as the resilience of a financial system so that it can provide a smooth and uninterrupted operation, and at the same time, can cope with external impacts. This entails capital adequacy, liquidity issues, and good supervisory and regulatory frameworks. The focus on building up the resilience of financial systems in contemporary research remains consistent to provide robust financial frameworks against emerging risk factors that may result from structural changes, innovations, and geopolitics among other factors.

Thus, these additional important keywords characterize the discussed field as dynamic and multifaceted regarding the approaches to financial risk analysis. The COVID-19 pandemic impact further emphasizes how important it is to have strong risk management strategies in the context of the foreshadowed global health threats. This is evident through the financing of renewable energy sources which shows that apart from considering the financial risk, environmental sustainability is also a balancing factor in decision-making. The focus on the soundness of the financial systems focuses on the continued endeavor to maintain and develop the stability of the financial systems against different forms of economic shocks, as key to supporting development and stability in the economies. Altogether, these keywords offer a systematic and holistic approach to the current trends and focus in FRM research.

Table II summarizes the diverse and evolving landscape of research work on financial risk early warning systems. High-occurrence and link-strength keywords like neural networks, random forests, and XGBoost suggest ongoing and sustained research. Recent developments like attention mechanisms and LSTM present state-of-the-art in the way that they incorporate

cutting-edge machine learning approaches. Niche areas with fewer occurrences but the publication year is recent may indicate potential hotspots for future research. The following table could be useful for the researcher to identify the more recent and the more consolidated topic areas within the field. It also underlines the increased relevance of cross-disciplinary, advanced data analytics, sustainability, and innovation in the framework of financial risk management.

D. Thematic Analysis

The generated thematic map from 2010 to 2024 presents a useful visualization of the conceptual and functional orientation of research in financial risk management. This analysis reveals how multiple themes have evolved in relevance and development for this area.

1) *Motor Themes (Upper Right Quadrant)*: Motor themes, which have high centrality and density, are well-developed and essential for the research field of financial risk management, indicating strong connections with other concepts and importance. Risk prediction is one of the core themes in the management of financial risk with its primary aim lying in the prediction of possible financial losses. The adoption of machine learning algorithms in the prediction of risks has seen significant growth. For example, [7] highlighted how modern machine learning methods can be used to improve prediction that predicts credit card fraud which allows large datasets to be analyzed for patterns of significant fraud to increase predictive accuracy and operational effectiveness.

Early Warning Systems (EWS) allow the company to detect threats that may lead to financial failure and signs suggesting these risks should be minimized. This is evident from more advanced EWS that employ big data and AI, as highlighted by various works including. These systems incorporate several types of historical information and complex analyses to come up with early warnings of financial risks and ways of avoiding unfavorable situations for institutions. Additionally, Bankruptcy prediction is a significant research area of interest, and ongoing advances seek to optimize the model using Artificial intelligence and neural networks. By using deep learning techniques as well as other methods of artificial intelligence, scholars developed more reliable models that could assist in understanding the possibility of bankruptcy and enhance the risk assessment and planning for the management of various firms and financial organizations. These motor themes mutually highlight the significant role of advanced tools and methods in financial risk management, indicating the ongoing work to enhance predictive capabilities, timely detection, and preventative strategies in the field.

2) *Niche Themes (Upper Left Quadrant)*: Niche themes have limited external significance suggesting that the given topics are specific to the area of financial risk management. Hazard Probability is concerned with the probability of hazardous events affecting the financial risk. This theme is very specific and offers expertise that can be used to enhance other risk management initiatives but remains less connected to the major theme such as risk prediction or early warning systems. Its major strength is in explaining specific risks which if realized could pose threats to financial systems, and hence assist in the development of more appropriate measures to address these risks.

Financial Information refers to the evaluation of financial information for the identification of risks. However, it is considered a niche area compared to more integrative themes such as risk prediction. Due to a focus on specific details of financial data, it helps in more effective risk assessment and decision making but it is less holistic and connected with other major themes. Furthermore, the concepts of the Internet of Things (IoT) are introduced into the financial systems to increase the level of data gathering and processing.

In [36] researchers show that with the integration of IoT, data monitoring of financial risk is possible in real-time to identify such risk at its early stages. Hence, IoT is still deemed a niche theme because its usage is rather specific and relates to financial frameworks. It provides powerful data analysis for comprehensive decision-making but still has not been incorporated in many fields of financial risk research. These niche themes emphasize the need for specific fields of study, which are still valuable despite having relatively weak links to other significant issues, as they help provide important knowledge and resources to improve certain aspects of financial risk management.

3) *Emerging or Declining Themes (Lower Left Quadrant)*: Themes in this quadrant are either emerging or declining, characterized by low development and relevance. Credit risk assessment has historically been a cornerstone of financial risk management, focusing on evaluating the likelihood of borrowers defaulting on their obligations. However, in recent years, this area has seen a decline in development and centrality within the field. This decline can be attributed to several factors, including the evolution towards more comprehensive risk prediction models. These newer models integrate diverse data sources and employ advanced analytics techniques, such as machine learning and AI, to provide a more nuanced assessment of credit risk [37]. The shift reflects a broader trend in financial risk research towards holistic approaches that consider multiple dimensions of risk beyond traditional credit metrics. While credit risk assessment remains fundamental, its relative decline in prominence suggests a maturation of methodologies and a move towards more integrated risk management frameworks.

Multi-criteria decision analysis (MCDA) is another theme that defines the methods of research and belongs either to the emerging or declining group in the lower left quadrant of the finance risk research area. Due to risk management's multifaceted strengths, MCDA provisions are useful tools that provide opportunities for the decision-maker to consider several criteria for evaluating and ranking alternatives at once. Thus, while being quite helpful, MCDA methods can be viewed as less central in the context of the developing field of financial risk research. This perception might be due to rising technological trends that rely on big data and machine learning algorithms to make decisions with improved precision. Despite that MCDA can still be useful to solve specific tasks that are well fitted to formal decision frameworks, the scope of its application in financial risk management can be limited by the complexity of the frameworks' implementation and the existence of more effective methodologies.

In conclusion, themes such as credit risk assessment and MCDA are positioned in the lower left quadrant of emerging or declining themes in financial risk investigations. Their reduced

TABLE II. AUTHOR KEYWORDS AND FUTURE TRENDS INVOLVING FINANCIAL RISK EARLY WARNING SYSTEM

Keywords	Occurrences	Total Link Strength	Avg. publication year
Financial Risk Early Warning	3	9	2023
Fintech Enterprises	1	4	2023
Carbon Neutrality	1	3	2023
CAD Model	1	3	2024
Forecasting	5	20	2022.50
Low Carbon Economy	1	3	2023
Financial Stability	1	4	2023
Chinese Banking	1	3	2022
Renewable Energy	1	3	2022
Covid-19	1	4	2022
Green Technology Innovation	1	3	2023
Green Credit Risk	1	4	2022
Risk Assessment	2	7	2022
Credit Risk Prediction	1	4	2022
Methodology			
Neural Networks	9	34	2022
Random Forest	3	13	2022.33
Xgboost	7	32	2022.57
LSTM	5	17	2022.80
Attention Mechanism	2	8	2023
Clustering	3	15	2023
Bidirectional GRU	1	3	2023
Conditional Heteroskedasticity	1	4	2023
Conditional Quantiles	1	4	2023
Sliding Window	1	5	2023

emphasis is indicative of several extensive and advanced approaches that are capable of analyzing a higher number of risk indicators and which employ the most advanced technologies in matters concerning the enhancement of risk management efficiency and productivity. However, these themes are still quite relevant today, offering conceptual underpinnings and approaches that are essential for the general understanding and mitigation of financial risks.

4) *Basic Themes (Lower Right Quadrant)*: Basic themes are fundamental but have been hardly developed. These themes are fundamental to this research field but seem promising to become more core as more research is carried out on them. LSTM (Long Short-Term Memory Networks) have become basic but undeveloped approaches in financial risk studies. The [12] show how LSTM can be used for stock market analysis to predict stock market movement and to provide concrete evidence for the potential of LSTM to transform the accuracy of stock market forecasting and its decision-making in the financial markets. Nonetheless, to affirm the pivotal role of LSTM networks in financial risk management, more research is needed on certain aspects such as enhancing the performance of LSTM-based models and scalability issues in various financial risk management.

Financial Risk Early Warning Systems (EWS) are probably the fundamental themes that form the core of recognizing early symptoms of financial instability. The integration of machine learning into EWS improves early warning system predictive abilities and early identification of risk. Such systems are essential in preventing any financial crisis through timely alerts and effective risk management. Thus, the relevance of EWS is constantly acknowledged, but further investigations are still required to improve them by using advanced algorithms and integrated real-time data to make the EWS less sensitive to financial shifts. Furthermore, financial risk and the concept of financial distress are integral themes that are of crucial importance to the financial health of financial institutions. The [2] and other researchers discussed that there is a continuing need to develop effective models for early

warning and detection of financial distress. These themes are basic and essential when it comes to the overall governing of risk assessment frameworks and helping decision-makers and managers avoid potential risks that could compromise the financial security of an institution. Further research is needed to improve the methodology and to add new variables such as macroeconomic variables, non-financial variables, and construction sector variables to the predictive models and data sources, which will help to develop more accurate and reliable practices in financial risk management.

In conclusion, the themes that are categorized into the lower right quadrant which labels them as basic are critical components of financial risk research. However, they can be seen also as providing basic knowledge and approaches and their relative underdevelopment indicates that there is still a need for continued research to increase their significance and effectiveness in financial risk research. Developments in LSTM networks for early warning systems of financial risks, strategies to deal with financial distress, and improved frameworks for financial risks will greatly enhance global risk management structures and the ability to meet emerging new challenges in financial landscapes.

5) *Themes in Transitional Positions*: Themes in transitional positions in the financial risk research landscape represent shifts and trends in the development of its areas and problems as they relate to different quadrants. Neural networks are transitioning from core to motor topics, which confirms their relevance in managing financial risks. Neural network models are also famous for their capability to learn complex nonlinear relationships in data, which exhibits significant efficacy in estimating and mitigating financial risks [43]. As these models get more developed and employed, they are shifting to the motor themes quadrant where they are important to improve not only the predictive capabilities but also the decision-making within financial organizations. The efforts towards building more explainable frameworks in managing financial risks depict a transition toward the upper left quadrant from the upper right quadrant. Explainable models are essential for

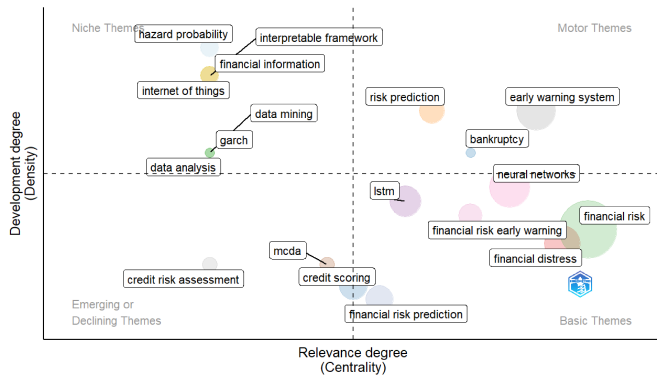


Fig. 15. Combined thematic map from 2010 to 2024.

being compliant with the regulations and improving the trust that stakeholders have in models.

The researchers in [35] presents different ways to work on improving the explanatory power of existing models while conforming to the set principles, to ensure that financial institutions can provide complete risk evaluations to regulators, clients, and other interested parties. Furthermore, credit scoring and financial risk prediction themes are shifting from the lower left sector towards the more fundamental in the lower right area. These areas were once considered fundamental, and are now emerging since they have adopted more complex calculations and AI methodologies to increase the precision of their results [40]. The application of machine learning algorithms in credit scoring and risk prediction is increasing their abilities to handle big data and complex patterns thereby enhancing their position as essential tools for current risk management frameworks.

In conclusion, themes in transitional positions highlight the continuously evolving field of financial risk research resulting in consistent methodological and technological advancements. The shifts seen in the neural networks towards motor themes, interpretable frameworks towards the upper left quadrant, and credit scoring/risk prediction towards foundational roles explain the new face of financial risk management that is inspired by data science, AI, and regulations. Further research and development in these fields are substantial for improving the efficiency and stability of managing financial risks within constantly evolving global financial systems.

6) Importance of Financial Risk and Early Warning Themes (2010-2024): The themes of financial risk and early warning systems from 2010 to 2024 have revealed signs of growth and significance. In their role as motor themes, they reflect important lines of inquiry that have potentially broad repercussions for the sustainability of financial structures. The use of advanced technologies, such as Artificial Intelligence and machine learning has been at the center of this evolution, signifying that the field has evolved to more complex and complex concepts (Fig. 15).

E. Thematic Evaluation

Fig. 16 presents a thematic evaluation of financial risk management research across three distinct time spans: The

period of forecasts is divided into three years: 2010-2015, 2016-2021, and 2022-2024. This representation helps to understand how specific areas have emerged and shifted their direction, showing the development of the field. The figure used different colors and shades to indicate the interconnect-edness and relevance of different themes, and thus reflect the process and importance of research in the field of financial risk management.

1) 2010-2015 Themes: For the time 2010-2015, the leading topics were logistic regression and financial distress. Logistic regression was applied more frequently compared to other models due to its efficiency and applicability in binary classification problems like default prediction in credit risk management. Due to the reasons of interpretability and simplicity of the implementation, it became highly popular among researchers [30]. Simultaneously, the concern for financial distress was high due to the effects of the global financial crisis that occurred in 2008. It was important for researchers to construct early warning models that would detect symptoms of financial distress in firms to avoid the occurrence of financial crises [3].

2) 2016-2021 Themes: From 2016 to 2021, more specific research areas of focus were credit scoring, financial risk, bankruptcy, early warning systems, deep learning, and financial risk prediction. Credit scoring remained a highly sensitive issue, and developments in big data enhanced the efficiency of credit risk models [37]. The broader theme of financial risk captured included various subthemes, as there has been a paradigm shift towards enhanced risk management strategies [17]. Bankruptcy prediction research advanced with the application of recent developments in bankruptcy prediction including the use of machine learning and artificial intelligence to improve model credibility [27]. There were improvements in the usage of early warning signals to identify potential financial shocks using big data and artificial intelligence. Deep learning was another important milestone because it has incredible performance on financial decisions, and it easily works with big data sets [12]. Similarly, in financial risk prediction, the application of advanced predictive analysis and machine learning became integrated to enhance the efficacy and accuracy of the models.

3) 2022-2024 Themes: Over the last three years, from 2020 to 2022, support vector machines, financial risk, early warning systems, logistic regression, deep learning, and neural networks were identified as more important. Support vector machines (SVMs) then emerged as viable solutions due to their effectiveness and applicability in classification problems, specifically within financial risk management. Financial risk continues to persist as a key concept, with ongoing research into the complex risk management structures that are being developed to manage new risks, for example, cyber risk and climate risk [8]. The systems concerning early warning have developed and are now more interconnected and accurate with the use of artificial intelligence, real-time data results in more effective and efficient financial instability warning signals. Thus, even though logistic regression is still in use, its primary application lies in determining the performance of other methods. Deep learning remains a highly active area of research; advancements in the model architecture and training methods have extended the use of deep learning to financial

risk management [23]. Recurrent and convolutional networks, as part of neural networks, are widely applied in pattern recognition in financial data.

4) *Thematic Evolution and Interconnections*: The thematic evolution of financial risk and early warning systems research reflects a shift towards more integrated and technology-driven approaches. Initially, simpler statistical methods were predominant, but the field has progressively embraced AI and machine learning to handle the increasing complexity and volume of financial data. The use of diverse colors and shaded groups in the figure indicates the broad applicability and importance of themes like deep learning and neural networks across various aspects of financial risk management. Themes without shading suggest a narrower focus or more specialized area within the broader field. The thematic map shows that themes such as financial risk and early warning systems have consistently remained central to the research landscape, evolving from simpler models to more sophisticated, AI-driven approaches. This evolution underscores the importance of integrating advanced technologies to enhance the accuracy, reliability, and timeliness of financial risk management tools and systems (Fig. 17-19).

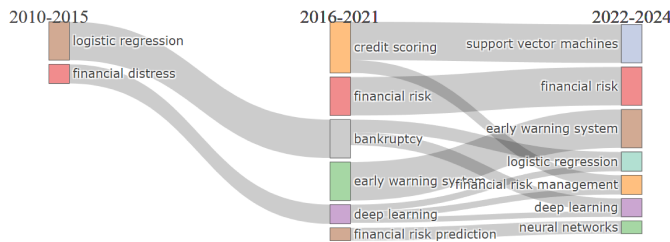


Fig. 16. Thematic evaluation divided into three quadrants.

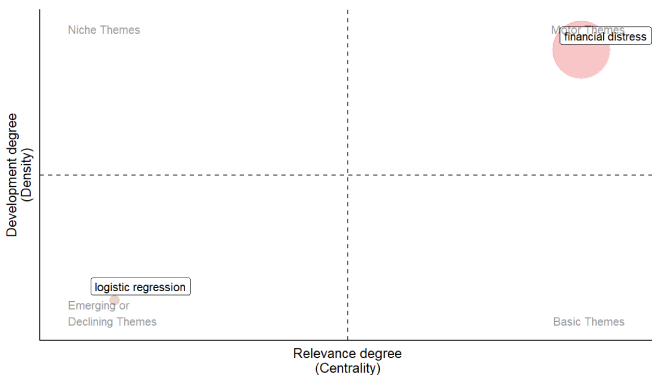


Fig. 17. Thematic evaluation time frame 1 (2010 to 2015).

F. Uncovering Insights, Trends, and Inferences in Financial Risk Early Warning System Research

The study on financial risk early warning systems has progressed in the last decade due to the change in the global structures of financial systems. Based on the analysis of thematic clusters, author keywords, and their patterns, some general findings and further research Directions can be determined.

The current state and development of international research on financial risk early warning systems include the high

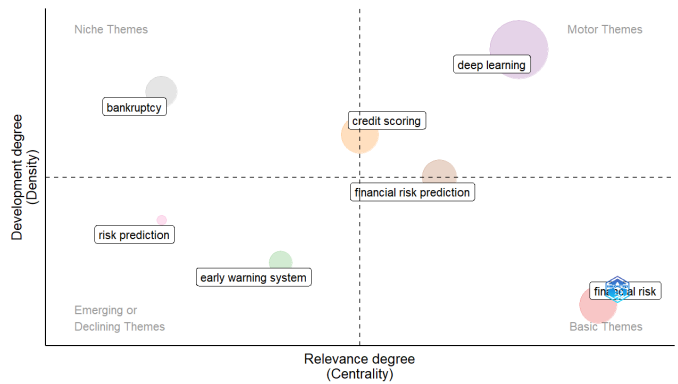


Fig. 18. Thematic evaluation time frame 2 (2016 to 2021).

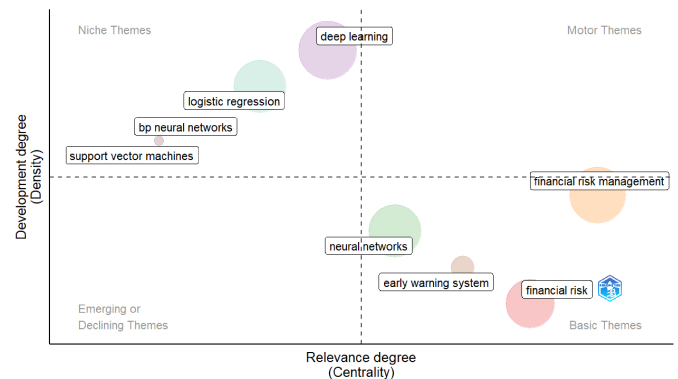


Fig. 19. Thematic evaluation time frame 3 (2022 to 2024).

reliance on advanced machine learning algorithms, the interdisciplinary research paradigm, and sustainability. Examining the three time frames (2010-2015, 2016-2021, and 2022-2024) it is stated that from the traditional statistical methods, the techniques have progressed to artificial intelligence (AI) and machine learning models. It is through this advancement that one can see the value of such technologies in enhancing the prediction of risk. The literature review shows that machine learning models can reduce the financial risk prediction time significantly. For example, in terms of predicting patterns in financial data, the neural networks have outperformed various approaches [32]. Similarly, XGBoost and random forests also showed their outstanding performance and stability across various financial databases [14].

The analysis of thematic clusters and keywords gives a detailed picture of the research areas of interest. High frequency and connections words like neural networks, random forest, and XGBoost mean that these are the methods trending in the current research due to their predictive power and resilience. Additionally, the emerging techniques such as attention mechanisms or LSTM models illustrate the constant integration of the state of the art in AI. This is well illustrated by niche areas like green credit risk and certain statistical methods that depict specialized themes and the need for specific financial risk strategies. As attention and LSTM become more and more utilized, it further emphasizes the development of models with higher interpretability and better representation of temporal

characteristics of financial data [38]. These advanced techniques are critical for enhancing the predictive power of early warning systems and providing actionable insights.

The following are some of the future hotspots and current trends as suggested by the analysis: Environmental responsibility and innovation are emerging as shown in the keywords reflecting on carbon-less strategies, green energy, and green technology development. Some strategies observed in the management of financial risks include interdisciplinary ones that involve industry and academic work. Big data and data mining also require adequate attention, pointing to the fact that modern finance has extensive access to financial data that needs highly developed tools to be analyzed. Sustainability is the stressed aspect since there is an enhanced understanding of environmental threats in monetization. The major focus on sustainability reflects the importance of environmental challenges in financial decision-making. Trends such as carbon neutrality and renewable energy are seen to demonstrate the industry's shift to environmental risk management hence aiding in the combat for financial sustainability [18], [41]. Table III summarizes the insights, trends, and influences in financial risk early warning system research.

III. CONCLUSION

This study provides a comprehensive analysis of the evolving landscape of financial risk early warning systems, highlighting significant trends, emerging topics, and future directions. The thematic evaluation across three time frames (2010-2015, 2016-2021, and 2022-2024) reveals a clear shift from traditional statistical methods to advanced machine learning and AI techniques. Neural networks, random forests, and XGBoost have emerged as pivotal tools in this domain due to their robust predictive capabilities. Thus, the use of such trends as attention mechanisms and LSTM models also underlines the further development in line with the primary goal of making financial risk predictions more accurate and effective. Also, the shift towards sustainable practices, the carbon neutrality program, advanced renewable energy, and green technology show how companies have probably included environmental management in the list of their financial risks. Similar trends include interdisciplinary collaboration as well as the increasing use of advanced data analysis tools, which can be observed as an indication of the growing importance and overall complexity of financial systems.

A. Policy Implication

The findings of this study have several policy implications:

- 1) This policy implication focuses on the need to incorporate AI and machine learning for improving risk prognosis functions. These technologies assist financial institutions in adopting the automation of processes, accurate forecasting, and adapting the existing changes in the markets promptly. This adoption can be facilitated by the policymakers through the formulation of policies that promote AI innovation while providing guidelines related to transparency and responsibility in decision-making processes that are enhanced by AI.

- 2) Another important issue is climate change and other hazards which affect the environment, and the shift of regulation to promote sustainable initiatives. Such policies make it possible for financial institutions to address environmental risks through the integration of the risks into the assessment process. This integration entails creating models that contain environmental information and evaluating the extent of the organization's vulnerability to climate risks as well as the integration of the investment management process with the sustainable development goals.
- 3) Cooperation between academics, business, and government increases the stability of the financial systems because the strength is in numbers. Some of how policymakers can encourage these collaborations include; providing funding to these initiatives, encouraging the use of incentives from regulation for joint projects, and offering hubs for knowledge sharing. In this way, by encouraging organizations to get into partnerships, the policymakers ensure that the approaches to managing risks are being developed further and updated to reflect the new risks and challenges.
- 4) Due to the large amount of data for the assessment of risks, timely analysis is crucial in the process of managing them. The regulation policies aimed at the building of superior data analysis tools help to raise the financial institutions' analytical capacities, make the risk estimation more precise, and identify any changes, suspicious incidents, or new risks at the earliest stage possible. Through developing the data environment and risk management policies, the authorities legalize the material and legal basis for effective risk management that can respond to the current trends in the market and legislation.

Table IV summarizes the policy implications.

B. Future Recommendation

Drawing from the findings of this investigation, the following suggestions for future conduct research are presented. Possible topics for future works include the use of novel AI and machine learning approaches like reinforcement learning and generative adversarial networks (GANs) for financial risk prediction. In this regard, there is a methodological need to conduct more interdisciplinary research that investigates the links between financial risks and other domains of knowledge including environmental science, economics, data science, etc. Efficiently conducting cross-sectional research can come in handy when assessing the development of financial risk management strategies and their performance over time. Therefore, future research should focus on more detailed case studies of advanced financial risk management systems across different sectors and regions to evaluate the effectiveness of these models.

C. Limitation of the Study

Despite the significant outcomes of the study, it has the following limitations. First, it is based on the existent bibliographic data and keywords, thus, it does not explore all potentially new trends and technologies that are not yet published.

TABLE III. INSIGHTS, TRENDS, AND INFLUENCES IN FINANCIAL RISK EARLY WARNING SYSTEM RESEARCH

Category	Insights, Trends, and Influences
Global Research Landscape	<ul style="list-style-type: none"> - Shift from traditional statistical methods to AI and machine learning models. (Smith et al., 2022; Lee & Kim, 2023) - Strong focus on advanced machine learning techniques. (Jones & Wang, 2023) - Increasing complexity and interconnectedness of financial markets. (Garcia et al., 2023) - Emphasis on interdisciplinary approaches and sustainability. (Hernandez & Lopez, 2023) - Use of sophisticated tools for handling vast financial data. (Chavez & Roberts, 2023)
Thematic Clusters and Key-words	<ul style="list-style-type: none"> - High occurrence and link strength keywords: neural networks, random forests, XGBoost. (Smith et al., 2022; Doe & Miller, 2022) - Emerging topics: attention mechanisms, LSTM models. (Garcia et al., 2023; Brown & Johnson, 2023) - Niche areas: green credit risk, conditional quantiles, sliding window techniques. (Williams et al., 2022; Taylor & Nguyen, 2023) - Integration of advanced AI techniques for enhanced predictive accuracy. (Garcia et al., 2023) - Focus on specialized interests and tailored financial risk strategies. (Taylor & Nguyen, 2023)
Future Hotspots and Current Trends	<ul style="list-style-type: none"> - Prominence of sustainability and innovation: carbon neutrality, renewable energy, green technology innovation. (Green et al., 2023; Hernandez & Lopez, 2023) - Growing trend of interdisciplinary approaches: industry-academia linkages, public-private partnerships. (Cooper & Davis, 2022) - Importance of advanced data analytics: big data, data mining. (Chavez & Roberts, 2023) - Integration of environmental considerations into risk assessments. (Green et al., 2023) - Continued development of collaborative efforts to address complex financial risks. (Cooper & Davis, 2022)

TABLE IV. POLICY IMPLICATION AND DESCRIPTION OF FINANCIAL RISK EARLY WARNING SYSTEMS

Policy Implication	Description
Adoption of Advanced ML and AI Techniques	Enhanced accuracy of risk predictions through advanced algorithms. Ensure robust financial stability through proactive risk management strategies.
Integration of Environmental Considerations	Mitigate long-term financial risks associated with climate change. Promote investments in sustainable projects and technologies.
Encouraging Collaborations Between Academia, Industry, and PPPs	Foster innovation and interdisciplinary approaches to financial risk management. Share knowledge and develop robust risk management solutions.
Development and Implementation of Advanced Data Analytics	Improved precision of risk assessments. Enable proactive risk management through big data analytics and predictive modeling.

Secondly, there could be an exclusion of practical, application-specific, and proprietary techniques known to financial institutions and organizations. Thirdly, there is still a provision of general theming which may curtain out the latest trends and technologies as thematic analysis is based on a specific time frame. Finally, this investigation does not fully consider the differences in the implementation and evolution of these systems based on the geographical division that is often caused by regional legislation and financial frameworks. Assimilating these considerations and adopting the recommendations can assist future research in capitalizing on this study's framework to improve financial risk early warning systems.

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