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Incorporating Green Bonds into Portfolio Investments: Recent Trends and Further Research

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Abstract: The analysis of green bonds and the composition of portfolio investments has gained importance in recent research. The current global context of Sustainable Development Goals requires investors to be environmentally, politically, and socially sustainable, in which the financing of green innovations has occupied a central role. Through the Web of Science and Scopus databases, we focused on analyzing recent trends and further research on green bonds into portfolio investments. The study was performed on 102 studies using Tree of Science (ToS), VOSviewer, and Bibliometrix techniques. We recognize the principal authors and sources, the most influential studies, and the bibliography coupling of studies and authors to identify their importance in the topic analysis. In order to expand the green bond market, particularly at the small and medium enterprise level, more policy instruments are needed. Thus, this study provides an extensive understanding of the research status of the analysis of green bonds and portfolio investments research as an essential input for market participants, researchers, policymakers, and decision-makers.

Keywords: bibliometric analysis; scientometric analysis; green bonds; sustainable finance; portfolio; SDG; green finance

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1. Introduction

The introduction of environmental, social, and governance (ESG) factors, which promote Sustainable Development Goals (SDGs), calls for a transition to a low-carbon economy [1]. As investors increasingly recognize the importance of sustainable and socially responsible investing, green bonds have become critical for mobilizing capital toward environmentally friendly projects. This type of bond enables issuers to raise funds specifically earmarked for projects that address climate change mitigation, renewable energy development, energy efficiency, and other environmentally beneficial activities [2–4].

By incorporating ESG factors, green bonds allow investors to support organizations demonstrating strong environmental stewardship, social responsibility, and sound corporate governance practices [5]. Including ESG criteria in evaluating and selecting investments reflects a growing recognition of the interconnectedness between financial performance and sustainable business practices.

Green bonds provide a mechanism to direct investment toward projects that contribute to achieving SDGs, such as affordable clean energy (SDG 7), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), and climate action (SDG 13). Furthermore, green bonds in portfolio investments are essential to support sustainable development, enhance diversification and hedging strategies, meet the growing demand for socially responsible investing, manage climate-related risks, and align with

regulatory and policy frameworks [6]. By integrating green bonds into their portfolios, investors can achieve financial returns and contribute to a more sustainable and resilient future. At this point, external and internal importance is based on the positive effects of global warming and raising financial resources with an environmental focus. Thus, as one of the main financial eco-innovations [7], green bonds are fundamental in a new economic era that allows economic growth with social and environmental outputs.

Conducting a comprehensive search on Scopus and Web of Science (WoS) using the keywords "green bond*" and "portfolio", our investigation yielded three prominent themes, as depicted in Figure 1. The first theme, represented by the color blue, encompasses sustainability, green finance, energy, and climate change. Here, we can find [8,9], by highlighting the significance of sustainability considerations and climate risk management in portfolio construction, these studies support the growing importance of ESG factors in investment decision-making. Understanding the connections between sustainable investments and conventional assets becomes crucial for constructing resilient and responsible portfolios as the world faces global challenges like climate change and economic uncertainty. The second theme, denoted by green, is linked to portfolio management, volatility spillovers, financial markets, oil prices, and co-movements. In this topic, we can include the studies carried out by [10–13], which focus on integrating green bonds into portfolio theory, examining risk dynamics, co-movements, causality relationships, and portfolio diversification benefits. Together, these studies contribute to advancing sustainable finance and responsible investing practices, addressing the challenges posed by environmental risks and fostering efficient capital allocation for environmentally and socially responsible assets.

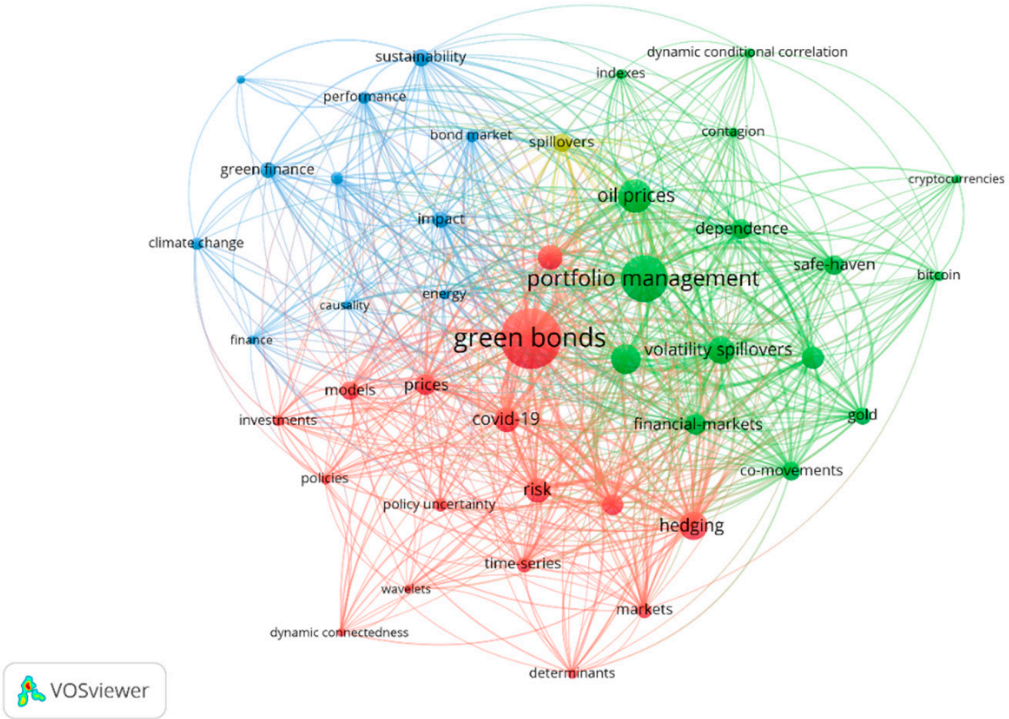


Figure 1. Network of co-occurring keywords for the search "dynamic linkage*" OR "dynamic co-movement*" OR "dynamic dependence*" OR "dynamic interdependence*". Source: Authors' own research using VOSviewer, as well as Scopus and WoS databases.

The third theme, represented by red, explores the intersections of COVID-19, risk, hedging, and policy uncertainty. For example, refs. [14–16] investigated the behavior of green bonds and their interactions with conventional financial assets in times of market volatility and uncertainty. The findings provide valuable insights to investors and portfolio managers, guiding them in constructing diversified and resilient portfolios during challenging market conditions, such as those posed by the COVID-19 pandemic. Additionally,

understanding the relationships between green bonds and other asset classes contributes to the ongoing development of sustainable finance and environmentally responsible investing strategies within the broader field of portfolio management.

By identifying these prominent themes and their interconnections, our research sheds light on the multifaceted nature of the literature on green bonds and its intersection with portfolio theory. This comprehensive overview provides researchers and practitioners with a roadmap for further exploration, enabling advancing knowledge in both fields. Understanding the relationship between green bonds, sustainability, portfolio management, risk, and policy uncertainty, especially incorporating green bonds into portfolio investments, is essential for developing robust investment strategies that integrate environmental considerations and align with sustainable development goals.

The objective of this research is to conduct a thorough scientometric study on the incorporation of green bonds into portfolio investments. The study aims to offer market participants, researchers, policymakers, and decision-makers a comprehensive understanding of the current state of the literature in this field. Furthermore, it identifies emerging research trends that can serve as a framework for driving further research and advancements in the field. This study presents a novel approach as it constitutes the first study utilizing scientometric and network analysis techniques, such as Tree of Science (ToS), VOSviewer, and Bibliometrix tools within the domain of incorporating green bonds into portfolio investments. Thus, this research addresses the following questions:

- RQ 1: What is the state of the knowledge of green bonds in investment portfolios?
- RQ 2: Who are the most influential researchers in the green bonds and investment portfolios arena?
- RQ 3: What are the fundamental studies to better understand the relationships between green bonds and investment portfolios?
- RQ 4: What are the main research trends?

By answering these questions, this study aims to contribute significantly to the existing literature and practice in three ways. First, it pioneers the integration of scientometric analysis using the Tree of Science (ToS), VOSviewer, and Bibliometrix tools to analyze the incorporation of green bonds into portfolio investments. These tools provide a solid framework for articulating and understanding the topic. Second, the study compiles and classifies a wide range of relevant literature on incorporating green bonds into portfolio investments, providing a comprehensive resource on the topic. Third, it demonstrates how the application of network maps and thematic cluster reviews can identify opportunities for further research, allowing the exploration of emerging themes from the empirical and theoretical literature.

The structure of this study is as follows. Section 3 provides an overview of the research approach employed and the strategy used for the literature search. Section 4 presents the results obtained using various scientometric methods, including knowledge maps, links, tables, and their interpretations. In Section 5, a comprehensive analysis of the empirical findings is presented and discussed. Finally, Section 6 summarizes the main results and conclusions from the scientometric analysis.

2. Literature Review

Green bonds are a type of financial instrument that has gained significant attention in recent years as a means to finance environmentally sustainable projects and initiatives. They are fixed-income securities in which the funds obtained from the bond issuance are exclusively used to finance projects that have positive environmental benefits. Furthermore, they are designed to align with the principles of sustainable financing and contribute to the transition to a low-carbon and sustainable economy [17].

The concept originated in 2007 with the issuance of the first green bond by the European Investment Bank [18]. Since then, the green bond market has experienced significant growth, with an increasing number of issuers and investors participating in this market. Global green bond issuance has seen explosive growth since 2013, and the Chinese green

bond market has made great strides, ranking at the top of global rankings [19]. This can be attributed to various factors, including the growing awareness of environmental issues, the need for investment in sustainable infrastructure, and the demand for socially responsible investment options [20].

In this regard, one key characteristic of green bonds is using funds. Unlike conventional bonds, where funds can be used for any purpose, green bonds have strict guidelines on allocating funds. The issuer must provide transparency and accountability by disclosing information about the projects to be financed and the environmental benefits to be achieved. This transparency is crucial for investors who want to ensure their contributions genuinely contribute to environmental sustainability [21].

On the other hand, research has shown that green bonds can positively affect corporate financial performance and stock prices [22]. Companies that issue them may experience an increase in the price of their stocks following the issuance announcement, indicating that investors perceive green bonds as a positive signal of the company's commitment to sustainability [23].

However, it is important to note that there are associated challenges and risks. One challenge is the potential for greenwashing, where issuers provide misleading information about their environmental commitment to gain a better public reputation and attract sustainability-oriented investors [24]. Another challenge is the perception of higher costs for issuers, as green bonds may require additional reporting and disclosure requirements. Additionally, the market remains relatively small compared to the global traditional bond market, and greater scalability and development are needed [25].

Therefore, the inclusion of green bonds in investment portfolios has been the subject of extensive research in the scientific literature. A study conducted by [26] examined the hedging and haven properties of green bonds in stock markets, both before and during the COVID-19 pandemic. Using the methodology proposed by [27], the researchers evaluated these bonds' hedging and safe haven characteristics. Their results demonstrated that green bonds offer diversification and present lower risk during economic stress and turbulence periods.

Additionally, they found that green bonds are an effective hedging option across different international equities, which has important implications for faith-based investors, ethical investors, policymakers, and regulatory bodies. The COVID-19 crisis and the global economic recession have had a negative impact on the green economy, jeopardizing sustainable development and neutrality goals. The authors in [8] conducted a study focused on examining the dynamic linkages between the green economy, sustainability, bitcoin, oil prices, and stock markets. Through empirical analysis methods such as Quantile-on-Quantile Regression (QQR) and Quantile Granger Causality methods, they found that the green economy and finance are sensitive to economic shocks, changes in oil prices, and overall sustainability changes. They also discovered a negative association between sustainability and oil prices, as well as between sustainability and stock markets in their portfolios.

In another study, ref. [28] examined the relationship between green bonds and green stock returns, concluding that despite their shared orientation toward environmental protection, they are two distinct types of financial assets with different return and risk profiles. This finding underscores the importance of considering the unique characteristics of these assets when constructing an investment portfolio.

On the other hand, ref. [29] focused on the volatility and conditional correlations between green bonds and gasoline prices in the United States, revealing a significant bidirectional relationship between green bonds and gas prices during bear market conditions. This suggests that policymakers should consider both interconnected markets when developing strategies, and that increasing the proportion of green bonds will support the transition to a low-carbon economy and diversify investment portfolios. Meanwhile, ref. [30] examined the effects of U.S. economic policy uncertainty, geopolitical threats and acts, and oil prices on green bond returns.

In their study, ref. [31] proposed a mediation model to analyze the influence of air pollution on green bonds. Their findings revealed that air pollution increases public concern, which drives investors' preference for green bonds and environmental responsibility. Additionally, ref. [32] conducted a study investigating the impacts of geopolitical, economic, and climate policy risks (GPR, EPU, and CPU, respectively) on conventional and green bonds' long-term returns and correlations.

In this regard, reviewing the existing literature on green bonds and various topics has experienced significant growth in recent years. This expansion in research has generated the need to apply bibliometric approaches to analyze and establish research trends in this emerging field, as they serve as quantitative analysis tools for scientific production, allowing the examination and evaluation of the evolution of publications related to green bonds. These analytical techniques provide a panoramic view of the publications, identifying research patterns.

3. Materials and Methods

We analyzed the existing literature on green bonds and portfolio investments. The relationship between green bonds and investment portfolios reflects the increasing awareness of environmental and social considerations in the investment landscape. By incorporating green bonds into their portfolios, investors can pursue both financial returns and positive environmental impact, making sustainable investing an essential aspect of modern portfolio theory [33]. Four scientometric techniques were implemented, which analyzed (1) studies, (2) bibliographic linkage, (3) authors, and (4) sources. The visualization of the research results was performed using Tree of Science (ToS), which is a bibliometric analysis tool formulated by [34], the VOSviewer software version 1.6.19 developed by [35], and the Bibliometrix package for R conceived by [36]. The scientometric techniques selected are employed to (i) identify the principal researchers, institutions, countries, and sources; (ii) identify the principal studies; and (iii) make a bibliography coupling to infer the emerging research topics in the area.

The selected scientometric tools have been extensively validated and widely adopted in the academic community, for example [12,13,37]. They are recognized for their accuracy, reliability, and ability to handle large datasets efficiently. VOSviewer and Bibliometrix offer a wide range of functions to extract, process, and analyze bibliometric data, allowing for an in-depth exploration of publication patterns, author contributions, and citation impact [38]. Using established tools like ToS, VOSviewer, and Bibliometrix enhances the reproducibility and transparency of the analysis, as other researchers can easily replicate the methods and validate the findings.

The academic databases used for publication search and selection were Scopus and Web of Science (WoS). The search equation was (TITLE-ABS-KEY (portfolio) AND TITLE-ABS-KEY ("green bond*")). The studies were obtained from Scopus and WoS as far as June 2023. All of these were downloaded and indexed into the Mendeley reference manager for reading and content analysis. Figure 2 illustrates the framework implementation of the current review. The study analysis and screening process consisted of removing duplicate records in the screening. After the screening process, 102 studies were included in the analysis.

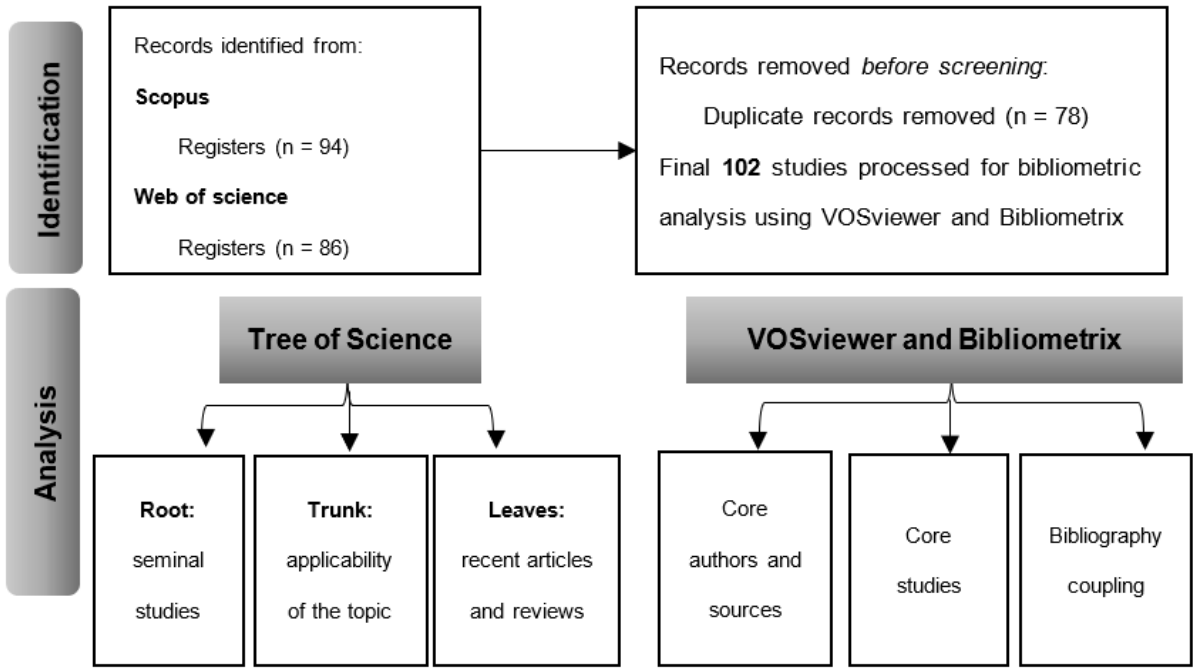


Figure 2. Literature search strategy.

4. Scientometric Analysis

4.1. General Information

In this study, 102 studies were identified, revealing 247 authors who contributed to the research. The average number of citations per study is 16.34, which is a significant recognition within the academic community. The importance of the subject is evident in the annual growth rate, which increased by 59.27% each year, highlighting its remarkable increase over time. Studies were the predominant study type, accounting for 84% of the total. In addition, a comprehensive analysis uncovered 211 KeyWords Plus and 298 author's keywords. For an overview of the study's results, see Table 1, which summarizes the essential details concerning the studies examined.

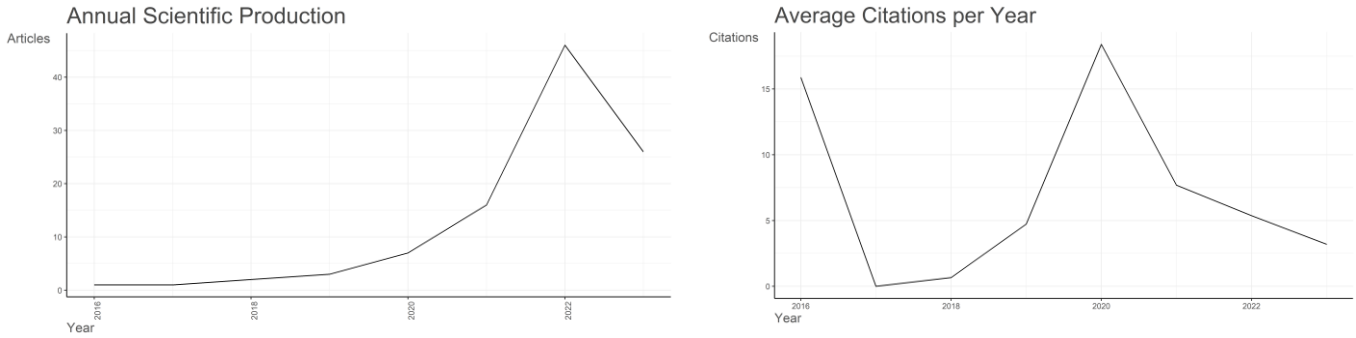
Table 1. Summary of the studies. Source: Authors' own research using the Bibliometrix tool, as well as Scopus and WoS databases.

Description	Results	Description	Results
Main Information		**Study Types (continued)**	
Timespan	2016:2023	Editorial material	1
Sources (journals, books, etc.)	59	Review	1
Studies	102	**Study Contents**	
Annual growth rate %	59.27	KeyWords Plus (ID)	211
Study average age	1.31	Author's keywords (DE)	298
Average citations per doc	16.34	**Authors**	
References	4919	Authors	247
Study Types		Authors of single-authored docs	9
Article	84	**Authors Collaboration**	
Article; early access	8	Single-authored docs	9
Book chapter	3	Co-Authors per Doc	3.16
Conference paper	5	International co-authorships %	53.92

4.1.1. Publication Output

Figure 3a exhibits a substantial increase in published studies, highlighting the growing interest in this topic within the academic community. The annual growth rate underwent a remarkable transformation, with a single study published in 2016 increasing to 46 studies in 2022. As of June 2023, 26 studies have been published on the subject, indicating an anticipated continuation of this upward trend throughout 2023 and beyond. However, it is

crucial to delineate the annual publication trends into two distinct periods. The research contributions were limited in the first period, extending until 2020, with fewer than seven studies published each year. The second period, from 2021 until June 2023, witnessed a significant surge in research contributions attributed to technological advancements to address the underlying issue. Furthermore, Figure 3b illustrates the average number of citations per year, revealing that 2020 achieved the highest average number of citations, accounting for 18.4% of the total.



(**a**) (**b**)

Figure 3. Scientific production and citations per year: (**a**) Publication output and (**b**) average number of citations per year. Source: Authors' own research using the Bibliometrix tool, as well as Scopus and WoS databases.

4.1.2. Most Relevant Sources

Figure 4 presents a comprehensive overview of the studies published by the most influential sources, ranking them in terms of their significance in researching green bonds and portfolio investments. The analysis reveals that this subject has garnered substantial scholarly attention, particularly in the esteemed journal *Energy Economics*, which accounted for nine publications. Following closely, *Finance Research Letters* emerged as the second leading journal, with seven occurrences. *Economic Modelling* and *Technological Forecasting and Social Change* secured the respective third and fourth positions as the most relevant journals, with five publications each. Lastly, the fifth and sixth positions were occupied by two international journals: *International Journal of Managerial Finance* and International Review of Financial Analysis, each with five occurrences.

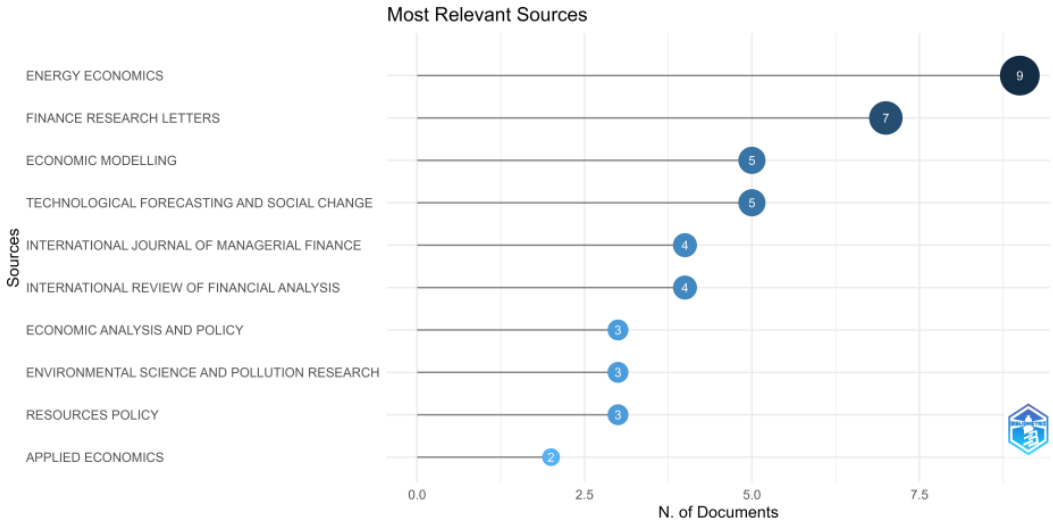
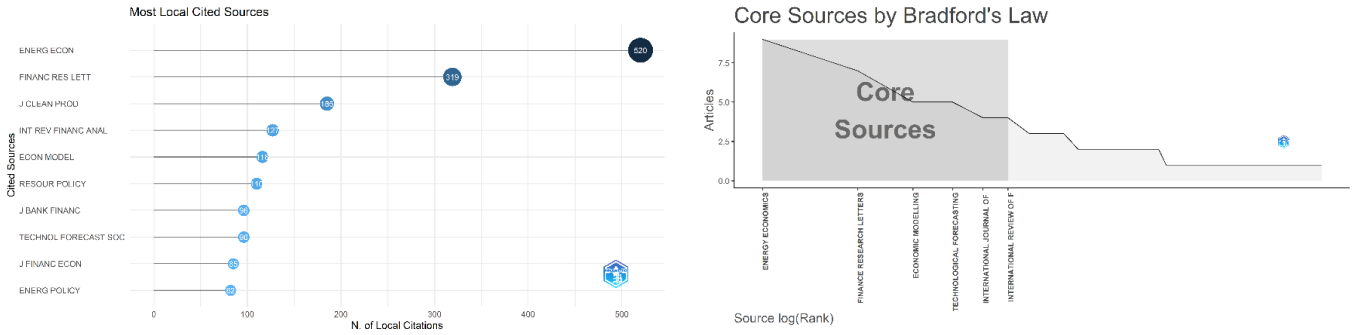


Figure 4. Most Relevant Sources of the studies. Source: Authors' own research using the Bibliometrix tool, as well as Scopus and WoS databases.

4.1.3. Most Cited Sources

This section critically examines the primary sources of substantial significance and influence in research concerning green bonds and portfolio investments. Figure 5a provides an illustrative representation of the distribution of the most cited sources. Notably, Energy Economics stands out at the forefront with a remarkable 520 citations, securing the top rank. *Finance Research Letters* follows closely behind with 319 citations, while *Journal of Cleaner Production* obtains the third position with 185 citations. Moreover, *International Review of Financial Analysis*, *Economic Modelling*, and *Resources Policy* make notable appearances with over 100 citations each, specifically amassing 127, 116, and 110 citations, respectively.



(**a**) (**b**)

Figure 5. Effect of the sources: (**a**) Most cited sources and (**b**) source clustering through Bradford's Law. Source: Authors' own research using the Bibliometrix tool, as well as Scopus and WoS databases.

To further evaluate the citation patterns, Bradford's Law [10] (Figure 5b) is employed, delineating the core and peripheral areas within the literature on this subject. The core area, known as Zone 1, encompasses the most frequently cited journals. In this context, *Energy Economics* maintains its prominent position with nine occurrences, followed by *Finance Research Letters* with seven occurrences. *Economic Modelling*, *Technological Forecasting and Social Change*, *International Journal of Managerial Finance*, and *International Review of Financial Analysis* also find representation in Zone 1, each appearing five times. Zones 2 and 3 encompass a broader range of journals, consisting of 20 and 33 entries, respectively. These findings underscore the importance of ensuring widespread access to scientific knowledge, enabling researchers to harness the collective understanding of the field.

4.2. Tree of Science Analysis (ToS)

According to [34], the ToS tool is developed through the analysis of citation networks, where studies are evaluated according to three indicators: (i) degree of entry, (ii) intermediation, and (iii) degree of exit. In the ToS, studies with a high degree of input and zero output are called roots. Meanwhile, studies with a high degree of intermediation are called trunk, and the items that determine the different perspectives of the topic have been referred to as branches. Finally, for visualization purposes, studies with high output and zero input are called leaves (see Figure 6). The studies and trends comprising the different parts of the ToS, which include green bonds in investment portfolios, are described below.

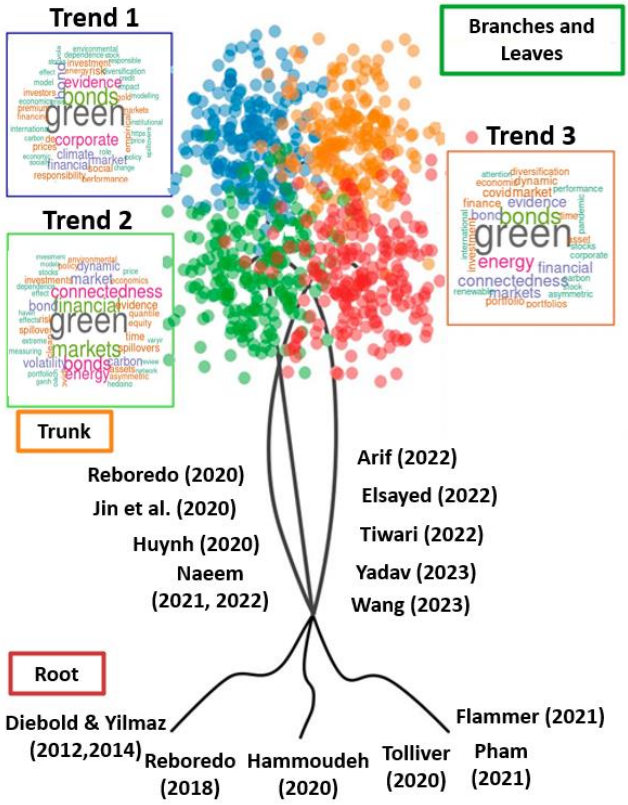


Figure 6. Tree of Science, which includes green bonds in portfolios, based on the theory of [34], using our research equation. Source: Authors' own research using the Bibliometrix tool, as well as Scopus and WoS databases [39–55].

4.2.1. Root

As indicated by [34], the studies at the root of the ToS can be identified as research supporting the relationship between green bonds and their incorporation in investment portfolios (see Figure 6). They are studies that describe, in a general way, the importance of the subject under study. Thus, the seminal studies from the original studies of our topic of interest are located at the root. Here, we find that the research conducted by [39,40] contains studies whose main topic is the analysis of connectedness as a central topic to risk measurement and management, which are widely cited in the literature. For instance, ref. [39] analyzed the volatility spillovers from the stock market to other markets after the collapse of the Lehman Brothers in September 2008. Moreover, ref. [40] studied the daily time-varying connectedness of major US financial institutions' stock return volatilities.

Furthermore, ref. [41] investigated the co-movement dynamics between the green bond market and financial markets, revealing that the green bond market demonstrates a coupling effect with corporate and treasury bond markets. Furthermore, our analysis indicates a weak co-movement between the green bond market and the stock and energy commodity markets. Additionally, ref. [41] observed that green bonds provide minimal diversification benefits for investors in corporate and treasury markets, whereas they offer substantial diversification benefits for investors in stock and energy markets. Additionally, ref. [42] employed a novel time-varying Granger causality test to investigate the dynamic causal relationship between green bonds and other assets, including US conventional bonds, the WilderHill clean energy (equity) index, and CO_2 emission allowances price. The findings reveal a significant causality from the US 10-year Treasury bond index to green bonds. Furthermore, ref. [42] identified a significant causal link between CO_2 emission allowance price and green bonds. Moreover, they observed a limited causal relationship between the clean energy index and green bonds. However, the findings indicate the absence of significant causality from green bonds to any of the considered assets, suggesting

a lack of predictive power within its respective domain. The analysis of [42] contributes to understanding the relationship between green bonds and various financial markets, as well as their potential diversification benefits and causal interactions. These insights can inform investment decisions, risk management strategies, and further research on sustainable finance.

Also, the study conducted by [43] provides evidence for the effectiveness and credibility of green bonds as a financial instrument for promoting environmental sustainability and attracting socially responsible investors. The findings have practical implications for companies considering green bond issuance, investors seeking sustainable investment options, and policymakers shaping the regulatory framework for sustainable finance. Furthermore, ref. [44] contributes to filling a gap in the empirical literature concerning the policies influencing green bond finance for renewable energy assets, which play a crucial role in achieving emissions reduction targets outlined in the Paris Agreement. By employing a difference-in-differences analysis and utilizing a unique panel dataset, this study assesses the impact of Nationally Determined Contributions (NDCs) on green bond finance. The results demonstrate that comparatively stringent NDCs, submitted after 2015, have a substantial positive effect on green bond allocations to renewable energy, highlighting the potential of climate commitments to drive global emission reductions by encouraging more significant financial support through green bonds. These findings provide valuable insights for policymakers, investors, and researchers working toward sustainable finance and achieving climate goals.

Finally, ref. [45] analyzed the frequency connectedness and cross-quantile dependence between the green bond and green equity markets. By examining different investment horizons and employing a cross-quantilogram framework, the study of [45] explores the dynamics and spillovers between these markets across various market conditions. The empirical findings reveal the nature of their dependence, highlighting that the connection between green bonds and green equity markets is relatively small during normal market conditions but becomes stronger during extreme market movements.

Additionally, the short-lived spillover effects and the dissipation of connectedness in the medium- and long-term investment horizons have important implications for environmentally conscious investors and policymakers. These insights contribute to a deeper understanding of the relationship between green bonds and green equity, aiding in developing investment strategies and policy frameworks that promote sustainable finance and environmental objectives.

4.2.2. Trunk

According to [34], the studies in the ToS trunk begin to shape the theory of including green bonds in investment portfolios. Thus, more specific studies on this topic have become benchmarks over time (see Figure 6). Among the studies with the highest degree of intermediation, the first to be found was the study conducted by [46,47], which contributed to the understanding of the relationship and behavior of green bonds in connection with other financial assets and its impact on portfolio allocation, emphasizing the importance of crisis periods, such as the COVID-19 pandemic, and providing insights for policymakers, investors, and regulatory authorities. The authors in [46,47] highlight the relevance of green bonds in portfolio allocation and risk management strategies, providing insights into their potential diversification benefits, crisis resilience, and evolving role in the investment landscape. It contributes to advancing portfolio theory by incorporating environmental factors and sustainable investment considerations into the portfolio decision-making process.

Likewise, ref. [48] examine the connectedness and dynamic correlations between green bonds and other asset classes. Its implications for portfolio design, hedging decisions, and the financing of a decarbonized economy make it a valuable addition to the existing literature on sustainable investing and portfolio management. Additionally, ref. [49] address the need for effective hedging instruments in carbon markets. It identifies the green bond index as a superior hedge for carbon futures, highlights the importance of

considering market dynamics, and emphasizes the superiority of dynamic hedge ratio models. This research contributes to understanding portfolio management in the context of environmental risks and provides valuable insights for investors and policymakers.

Similarly, the study conducted by [50–54] contributed to understanding the connectivity, risk transmission, and portfolio implications of green bonds, carbon pricing, and renewable energy stocks, among others. They highlight the importance of considering socially responsible investment practices, the potential of green bonds as hedging and diversification instruments, and the role of these assets in the global financial recovery and transition to a low-carbon economy. They also contribute to understanding the interconnectedness between green bonds, renewable energy stocks, and other financial assets. They provide empirical evidence, highlight the impact of the COVID-19 pandemic, and address policy implications related to socially responsible investments and climate-related financial risks. These insights can inform investment decision-making processes and contribute to developing portfolio theory concerning sustainable and interconnected financial markets.

Finally, ref. [55] explored the role of artificial intelligence (AI), robotics stocks, and green bonds in portfolio diversification, its analysis of volatility connectedness and transmission, and its implications for risk management and diversification strategies. By incorporating these insights, portfolio theory can continue to evolve and adapt to the changing landscape of financial markets in the context of the fourth industrial revolution, AI, and environmental challenges.

4.2.3. Branches and Leaves

The different perspectives found are located in the part of the branches and leaves of the ToS. The branches and leaves show a higher density in the structure of the network; they are studies that deal with a subtopic of the inclusion of green bonds in investment portfolios. The result of the analysis showed three research trends in which the topic is divided: (i) sustainable financial markets, (ii) connectedness between green bonds and other financial assets, and (iii) green bonds and portfolio analysis (see Figure 6).

The first trend that studies sustainable financial markets includes the analysis of [9,28,56,57], which examines the coherence of extreme returns, assessing the impact of climate uncertainty, investigating the influence of environmental factors, exploring time-varying risk spillover and dependence, analyzing the performance of green bonds, and studying the relationship between sustainable investments and uncertainties. The studies provide valuable insights for portfolio allocation, risk management, and integrating sustainable assets into investment strategies. For example, ref. [28] examines the coherence of extreme returns between green bonds and a set of green stocks. The study explores the dependency between these assets by employing novel estimation techniques such as quantile spectral coherency models, cross-quantilogram correlation approach, and windowed time-lagged cross-correlation. This analysis contributes to understanding the risk and return characteristics of green bonds and stocks, shedding light on their potential role in portfolio diversification.

Additionally, ref. [9] focuses on the effect of climate uncertainty on spillover effects across conventional and environmental, social, and governance (ESG) financial markets. The study demonstrates the diversification benefits that ESG investments can offer conventional investors against climate-driven shocks by analyzing the shock transmissions during periods of high climate uncertainty. This finding has implications for portfolio managers seeking to manage climate risk exposures and highlights the role of climate uncertainty in informational spillovers between different asset classes. Furthermore, ref. [57] explores the relationship between sustainable investments and a series of uncertainties, including economic and political turbulences and the COVID-19 pandemic. By using Rényi's transfer entropy method, the study measures the information flows and relationships between different uncertainties and environmental, social, and governance (ESG) portfolios. This methodology adds to the existing literature and provides insights into decision making dur-

ing turbulent times, enhancing our understanding of the dynamics between uncertainties and sustainable investments.

In the second trend, concerning the connectedness between green bonds and other financial assets, we can consider the research developed by [12,13,29,58,59]. For example, the studies conducted by [12,13] contribute to understanding the relationship dynamics, causalities, and interdependencies among green bonds, CO_2 emissions, and oil prices. The findings suggest that green bonds negatively affect CO_2 emissions and oil prices. Additionally, Brent oil returns positively impact the forecasts for CO_2 futures' returns. Then, the CO_2 futures' price can be forecasted according to the oil price evolution in the international markets. Finally, the studies contribute to the evolution of portfolio theory by highlighting the importance of sustainable investments, the impact of environmental factors, and the complex relationships within the green bonds market. This knowledge assists portfolio theorists in developing investment strategies that integrate environmental considerations, manage risk, and seek sustainable financial performance.

Moreover, refs. [29,58,59] examine the return connectedness, tail dependence, dynamic relationships, drivers of return spillovers, optimal asset allocation opportunities, and coherence of extreme returns within the context of green bonds, Sukuk, carbon futures, and green stocks. These insights enhance the understanding of portfolio construction, risk management, and the integration of sustainable and climate-related assets into investment strategies.

Finally, the third trend explicitly explores our study's object: green bonds and portfolio analysis. Here, we find the research developed by [10,11,14,60–64]. Firstly, for example, refs. [11,60,61] provide valuable insights into the growth, composition, risk, return characteristics, co-movements, and diversification benefits within investment portfolios. By analyzing the integration of green bonds into portfolios and their impact on risk, return, and stability, these studies contribute to the evolution of portfolio theory and inform portfolio managers, policymakers, and socially responsible investors in their decision-making processes related to sustainable and responsible investment practices.

Additionally, the role of green bonds in portfolio diversification, risk mitigation, and hedging strategies during economic uncertainty is explored. The findings offer insights into the potential benefits and implications of incorporating green assets into investment portfolios, expanding the understanding of sustainable and resilient investment strategies. Finally, refs. [10,62] contribute to the evolution of portfolio theory by examining portfolio construction techniques, risk dynamics, dependence structures, and diversification benefits within specific asset classes.

Furthermore, the empirical evidence presented by [64–66] supposes the notion that portfolios containing green bonds outperform conventional bonds regarding risk-adjusted returns. This underscores the importance of incorporating green bonds into investment portfolios, allowing investors to achieve superior performance while addressing environmental sustainability goals. The findings contribute to the development of portfolio theory by highlighting the benefits of integrating environmental considerations into portfolio construction and asset allocation decisions.

The studies discussed in this section provide insights into research conducted on optimal portfolio models that include green bonds and point to further research; for example, risk management strategies and asset allocation approaches, considering extreme events, dynamic hedging, and interrelationships between different asset classes.

4.3. Core Authors

4.3.1. Most Relevant Authors

Figure 7a visually represents the top 5 authors who have significantly contributed to the research on incorporating green bonds into portfolio investments. These authors are ranked based on the number of published studies, and are depicted as follows: (i) Tiwari, (ii) Abakah, (iii) Naeem, (iv) Agliardi, and (v) Adekoya. Furthermore, Figure 7b showcases the temporal evolution of these authors' productivity. The graph employs color intensity to

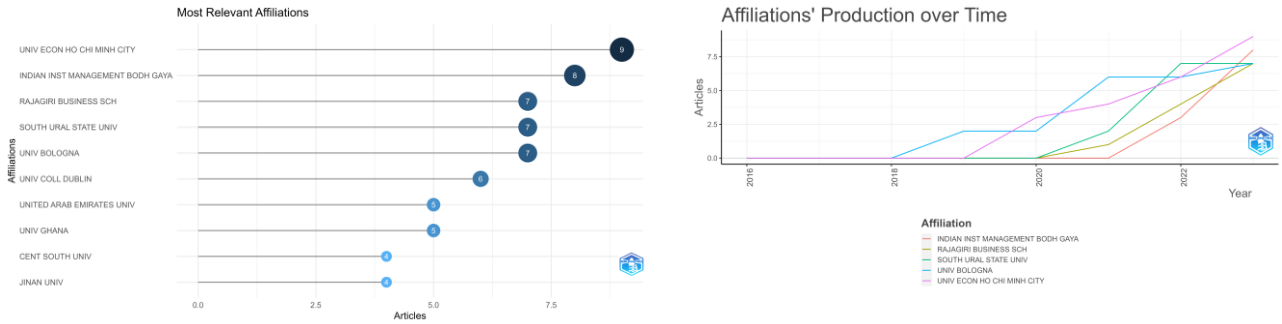
ind5icate the citation year, while the bubble size corresponds to the number of publications by each author in a given year. For instance, in 2021, Tiwari [52] published his initial study on this topic. Subsequently, in 2022, the same author contributed four studies to this subject, and, in 2023, six studies were published by Tiwari.

(**a**) (**b**)

Figure 7. Productivity of the authors: (**a**) Number of publications by Authors and (**b**) Authors' Production over Time. Source: Authors' own research using Bibliometrix tool, as well as Scopus and WoS databases.

4.3.2. Most Relevant Authors' Affiliation

Figure 8a presents a visual representation of the top five institutions that have significantly contributed to research on incorporating green bonds into portfolio investments. These institutions are ranked based on the number of studies they have published and include the following: (i) University of Economics Ho Chi Minh City, (ii) Indian Institute of Management Bodh Gaya, (iii) Rajagiri Business School, (iv) South Ural State University, and (v) Università di Bologna.



(**a**) (**b**)

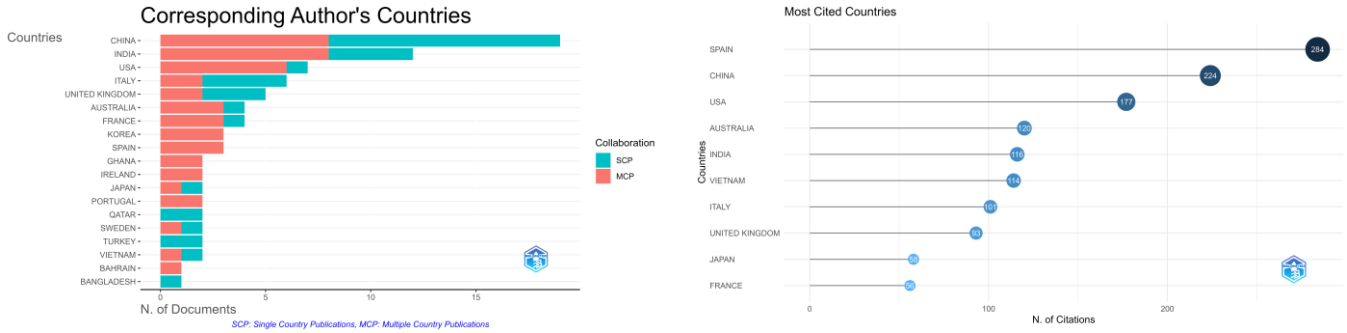
Figure 8. Affiliation of the authors: (**a**) Most Relevant Affiliations and (**b**) Affiliations' Production over Time. Source: Authors' own research using Bibliometrix tool, as well as Scopus and WoS databases.

Furthermore, Figure 8b depicts the temporal evolution of these institutions' research productivity. The graph provides insights into the publication trends of these institutions over time. For instance, in 2020, the University of Economics Ho Chi Minh City published three studies on this topic. In the subsequent year, the institution contributed one study, followed by two studies in 2022. Finally, in 2023, the University of Economics Ho Chi Minh City published three studies, bringing this institution's total number of publications to nine.

4.3.3. Author's Country Analysis of Correspondence

Figure 9a visually presents the countries of corresponding authors who have significantly contributed to the research on incorporating green bonds into portfolio investments. Notably, China emerged as the most contributing country, followed by the United States,

Italy, and the United Kingdom. China demonstrates a substantial presence in this research domain, with approximately 58% of the publications originating from a single country (SCP) and 42% from multiple countries (MCP). Conversely, countries such as South Korea, Spain, Ghana, and Ireland primarily contribute to SCP without significant involvement in MCP. In contrast, India and the USA exhibit a higher proportion of MCP compared to SCP. These findings offer insights into collaboration patterns and research networks among countries involved in the study of green bond incorporation.



(**a**) (**b**)

Figure 9. Author's country analysis of correspondence: (**a**) Corresponding Author's Countries and (**b**) Most Cited Countries. Source: Authors' own research using Bibliometrix tool, as well as Scopus and WoS databases.

Furthermore, Figure 9b highlights the most cited countries in this field, with Spain leading the pack with 284 citations, followed by China, the USA, Australia, and India. The prominence of these countries in terms of citation count signifies the influence and recognition of their research within the scholarly community. Their contributions have significantly advanced knowledge in incorporating green bonds into portfolio investments. This information underscores their noteworthy impact on the development of knowledge in this specific area.

Figure 9a,b provide valuable insights into the countries leading in research output and citation impact within the context of green bond incorporation in portfolio investments. Understanding these patterns is crucial for identifying key contributors, fostering collaboration, and acknowledging the influential research outputs contributing to advancing knowledge in this field.

4.3.4. Co-Author Analysis

In the analysis of co-authors, the number of research studies in which two or more researchers have collaborated is a crucial consideration. Visualizing this information on a map helps depict the connections between these researchers through colored lines, representing the links among the items. The weight attributes assigned to each item's size indicate the importance of the identified network. Furthermore, the number of lines connecting co-authors reflects their relevance within the analyzed bibliographic dataset [67].

Figure 10 provides a graphical representation of the connections between researchers based on their collaborative efforts in producing joint studies. This figure enables the examination of collaboration networks and identifies potential author groups focused on studying the dynamic association between assets in financial markets. The network analysis reveals the involvement of 247 authors and the formation of 17 links distributed among five clusters. Although these clusters exhibit considerable dispersion, several research co-authorships can be discerned, such as Naeem [47,68], Tiwari [52], Abakah [29,69], Bouri [70,71], and Elsayed [54]. This visual representation offers insights into the existence and characteristics of collaborative networks. It sheds light on the collaborative dynamics among researchers investigating incorporating green bonds into portfolio investments. All

these studies highlight the importance of green bond relationships with risk, dynamic price correlation, energy stocks, and conventional assets, among others.

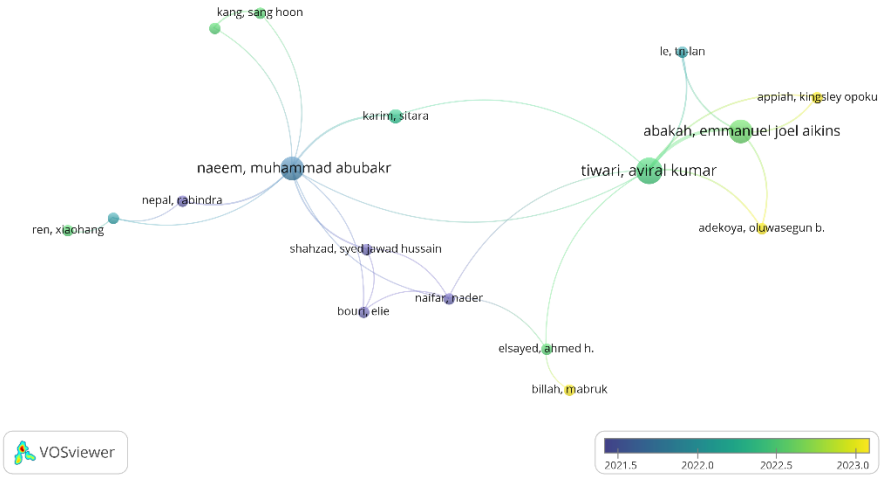


Figure 10. Co-authorship network. Source: Author's own research using VOSviewer, as well as Scopus and WoS databases.

4.4. Core Studies

4.4.1. Most Influential Publications

The fundamental premise that underlies the citation analysis is that citations indicate the impact exerted by the cited study [72]. Consequently, citation analysis is a fundamental tool for assessing the impact and influence of scholarly works. It provides a quantitative measure of recognition within the academic community and contributes to the advancement of knowledge by revealing influential studies, authors, or journals. Additionally, it aids in understanding the dynamics of research fields and supports evidence-based decision making in academic institutions [72].

Table 2 presents the top 10 globally cited studies, which predominantly center their analysis on two key dimensions: (i) hedging analysis ([26,49,52]) and (ii) price connectedness and volatility spillovers ([48,55,58,73–76]). These dimensions collectively capture the impact of incorporating green bonds within portfolio analysis and underscore their influence on various aspects of portfolio dynamics.

Table 2. Top 10 most globally cited studies in the research on green bonds and their incorporation in investment portfolios. Source: Authors' own research using Bibliometrix tool, as well as Scopus and WoS databases.

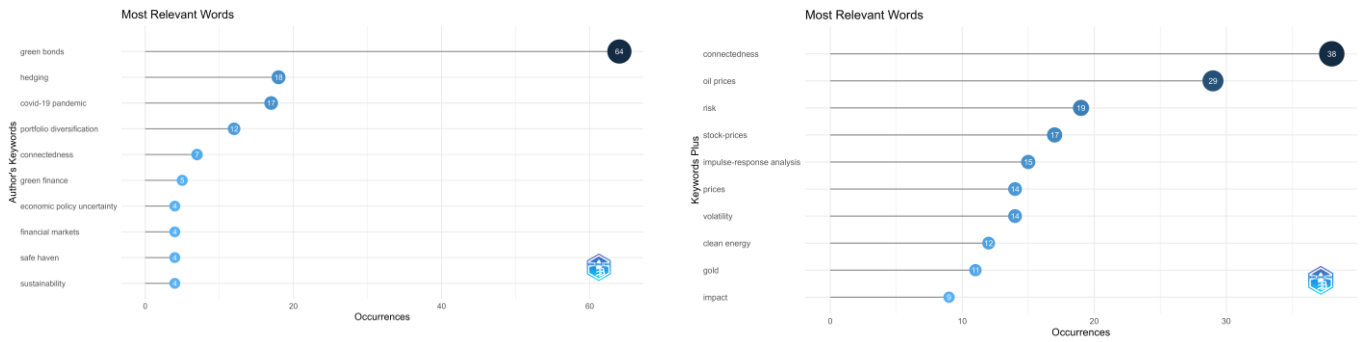
	Author	Source	Total Citations	TC per Year	Normalized TC
1	Reboredo and Ugolini [73]	*Economic Modelling*	163	40.75	2.22
2	Pham [75]	*Journal of Sustainable Finance and Investment*	127	15.88	1.00
3	Le, Abakah, and Tiwari [74]	*Technological Forecasting and Social Change*	115	38.33	4.99
4	Reboredo, Ugolini, and Aiube [48]	*Energy Economics*	113	28.25	1.54
5	Huynh, Hille, and Nasir [55]	*Technological Forecasting and Social Change*	104	26.00	1.41
6	Jin et al. [49]	*International Review of Financial Analysis*	78	19.50	1.06
7	Tiwari et al. [52]	*Global Finance Journal*	78	39.00	7.26
8	Ren et al. [58]	*Technological Forecasting and Social Change*	58	29.00	5.40
9	Agliardi and Agliardi [76]	*Environment and Development Economics*	55	11.00	2.32
10	Naeem et al. [26]	*International Journal of Islamic and Middle Eastern Finance and Management*	54	54.00	16.92

The findings are predominantly consistent with the studies identified in the ToS, except for the new studies identified as [73–76], which discuss several aspects related to the linkages between green bonds and financial markets, including price connectedness, risk management implications, volatility behavior, and determinants of green bond value.

The findings contribute to the evolution of portfolio theory by shedding light on the characteristics, behavior, and potential benefits of incorporating green bonds in investment portfolios. For instance, the findings in [73] have important implications for portfolio and risk management decisions, particularly for environmentally aware investors in green bonds. Furthermore, ref. [74] highlights the potential role of traditional assets, such as gold, oil, and green bonds, as proper hedging instruments due to their lower shock transmissions to other assets. Additionally, the insights in [75] are valuable for asset pricing, portfolio management, and risk management considerations, providing a better understanding of the behavior of the green bond market. Finally, ref. [76] highlight the policy implications, suggesting that improvements in credit quality can lead to lower capital costs for green bond issuers, and governmental incentives and investors' green awareness play a significant role in scaling up the green bonds market.

4.4.2. Most Frequent Keywords

Figure 11 presents the most frequent keywords, including authors' keywords and KeyWords Plus, from 2016 to 2023 (June). Analyzing authors' keywords provides valuable insights into research trends from the researchers' perspective [53]. On the other hand, KeyWords Plus are terms extracted from titles or abstracts [36]. Both author's keywords and KeyWords Plus play important roles in comprehensively understanding the keywords corresponding to the studies' contents. Author's keywords provide insights into the authors' specific research focus and intentions, while KeyWords Plus offers a broader perspective by capturing related terms and concepts. To gain a comprehensive understanding of a research topic, it is beneficial to consider and analyze both sets of keywords together. The analysis of these two keywords reveals that "connectedness" is the one most commonly used.



(**a**) (**b**)

Figure 11. Most frequent keywords: (**a**) Author's keywords and (**b**) KeyWords Plus. Source: Authors' own research using Bibliometrix tool, as well as Scopus and WoS databases.

Figure 11a displays the authors' keywords, which offer clues about the primary focus of the research on incorporating green bonds into portfolio investments. Notably, "green bonds" emerges as the most prevalent keyword, appearing 64 times. It is followed by "hedging" with 18 occurrences. In the third place, the "COVID-19 pandemic" is mentioned 17 times, and "portfolio diversification" is mentioned 12 times, occupying the fourth position. These keywords provide insights into the main areas of analysis in research related to incorporating green bonds into portfolio investments.

Figure 11b showcases KeyWords Plus, which encompasses the fundamental literature related to the analysis of green bonds and portfolio investments. Accordingly, the prominent topics explored in this research area include "oil prices", "risks", "stock prices", and "impulse-response analysis". These keywords shed light on the key areas of investigation and provide a broader understanding of the literature surrounding the analysis of green bonds and portfolio investments.

4.4.3. Thematic Map

The analysis depicted in Figure 12 provides a thematic map that categorizes the research into four topic quadrants, determined by the density and centrality of the issues under investigation. It is important to note that the themes in the upper-right quadrant warrant deeper examination and study due to their high density and centrality within the research landscape [77,78]. Eight major clusters were identified in terms of the authors' keywords analyzed, while six were identified within the KeyWords Plus. These clusters offer a comprehensive framework for understanding the key thematic areas and focal points within the research on incorporating green bonds into portfolio investments. We will focus only on the topics with high relevance and density for our analysis.

(**a**) (**b**)

Figure 12. Thematic map: (**a**) Author's keywords and (**b**) KeyWords Plus. Source: Authors' own research using Bibliometrix tool, as well as Scopus and WoS databases.

Figure 12 identifies the most promising areas for further research in the analysis of incorporating green bonds into portfolio investments. By examining the author's keywords (Figure 12a) and KeyWords Plus (Figure 12b), researchers can gain valuable insights into the critical areas of interest that require further investigation.

In the case of the author's keywords (Figure 12a), two specific areas stand out as particularly promising for further research: (i) energy efficiency and OECD countries; and (ii) green bonds, hedging, and the COVID-19 pandemic. The first area pertains to energy efficiency and its relationship with OECD countries, suggesting a need to explore the intersection of green bonds and energy efficiency within the context of economically developed nations. The second area emphasizes the importance of studying green bonds, hedging strategies, and the impacts of the COVID-19 pandemic, indicating a call for research on how these factors interact and influence portfolio investments.

Moreover, the analysis of KeyWords Plus (Figure 12b) reveals four key areas that hold significant potential for future research in the analyzed topic (i) sustainability, corporate social responsibility, and costs; (ii) transmission, volatility spillovers, and electricity; (iii) models, economy–policy uncertainty, and environmental regulation; and (iv) impact, bond, and energy. The first area encompasses sustainability, corporate social responsibility, and associated costs, examining the broader implications and financial aspects of incorporating green bonds into portfolio investments. The second area highlights the relevance of transmission, volatility spillover, and electricity, pointing toward exploring the transmission mechanisms and market dynamics between green bonds and other financial instruments.

The third area emphasizes the need to examine models, economy–policy uncertainty, and environmental regulation, indicating the importance of developing robust models and considering policy uncertainties when studying the issuances of green bonds [79]. Lastly, the fourth area underscores the impact of green bonds on the bond market, energy sector, and their interactions. Studying the impact of green bonds on the bond market, energy

sector, and their interactions is crucial for understanding market dynamics, assessing sustainable finance efforts, guiding investor decisions, informing policy development, and promoting social and economic development [4]. Such research enhances our knowledge of the role of green bonds in transitioning toward a more sustainable and resilient future [25].

Overall, the information presented in Figure 12 provides researchers with valuable guidance on the most promising avenues for further analysis of the incorporation of green bonds into portfolio investments. By addressing these areas, researchers can help advance the knowledge and understanding of this evolving field.

4.4.4. Thematic Evolution

Thematic evolution is a bibliometric technique that provides a historical perspective on research and contributes to a science-based paradigm for guiding future research themes [78,80]. This approach focuses on identifying the most significant research themes and their evolution over time, offering valuable insights into the future trajectory of the field [81]. In the context of studying the incorporation of green bonds into portfolio investments, Figure 13 depicts the progression of the most frequently used terms by authors from 2016 to 2023 (June).

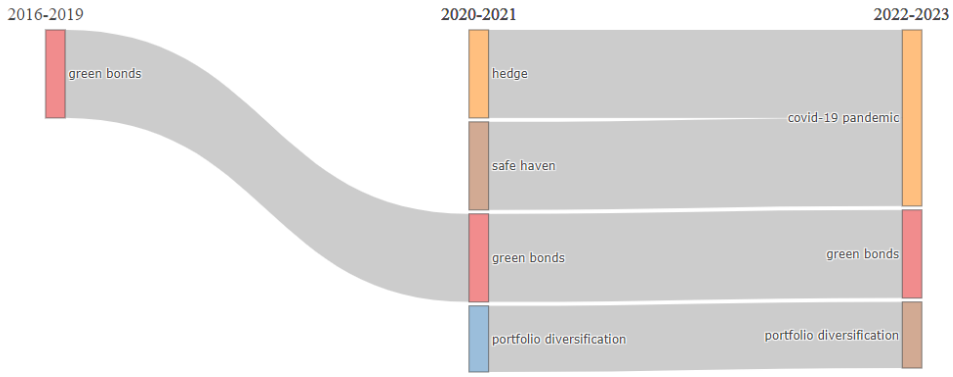


Figure 13. Thematic evolution of author's keywords. Source: Authors' own research using Bibliometrix tool, as well as Scopus and WoS databases.

Two specific cutting points were selected to capture the key milestones and changes in the field: 2019 and 2021. These points mark significant events within the sample period, including the emergence of the early literature on green bonds, the global impact of the COVID-19 pandemic, and the most recent developments in 2022–2023 (June). Figure 13 provides a visual representation of the changing research landscape by analyzing the evolving usage of terms over time. It highlights the important themes that have emerged and developed throughout the study period.

Furthermore, the authors' keywords are utilized to provide insights into the authors' specific research focus and intentions [82]. The dimension of the boxes in Figure 13 represents the frequency of keyword appearance, providing a visual representation of the prominence of different topics.

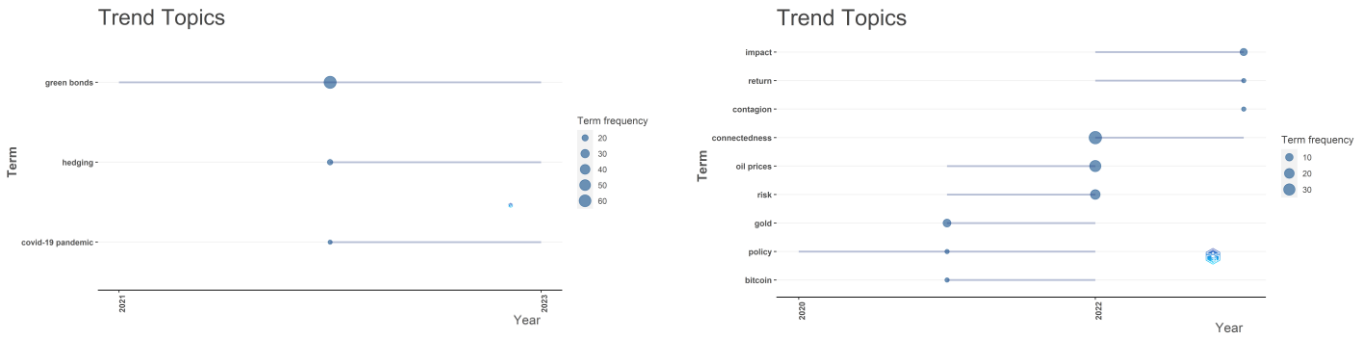
From 2016 to 2019, the dominant keyword was "green bonds", indicating that research efforts were primarily focused on including green bonds in financial markets as a significant aspect of financing green investments. In the subsequent time slice (2020–2021), this topic expanded into four branches: hedge, safe haven, green bonds, and portfolio diversification. These four keywords represent the additional topics of interest during that period, indicating the evolving research landscape and exploring different aspects of green bond incorporation.

The mention of "hedge" and "safe haven" is commonly associated with the COVID-19 pandemic in 2022–2023, suggesting a shift in research focus toward understanding the impact of the pandemic on the relationship between green bonds and risk management strategies. Furthermore, the consistent presence of "green bonds" and "portfolio diversification" across the periods from 2020–2021 to 2022–2023 indicates these topics contin-

ued relevance and importance in the research on incorporating green bonds into portfolio investments.

4.4.5. Trend Topics over the Years

The application of a trending topic analysis serves as a crucial mapping tool in illustrating the progression of the literature. Figure 14 provides an overview of the identified topics based on authors' keywords and keyword plus, with a minimum frequency of five words per study, analyzed three times a year. This analysis holds significance in tracking the development and trends within the research field.



(**a**) (**b**)

Figure 14. Trend topics over the years: (**a**) Author's keywords and (**b**) KeyWords Plus. Source: Authors' own research using Bibliometrix tool, as well as Scopus and WoS databases.

The analysis of the authors' keywords reveals the prominent themes that have emerged between 2021 and 2023, including green bonds, hedging, and the COVID-19 pandemic. Then, according to the authors, these research topics have an essential relevance and significance during this period. On the other hand, the keyword plus analysis indicates that specific keywords have gained popularity between 2020 and 2023, including impact, return, contagion, connectedness, oil prices, risk, gold, policy, and bitcoin. These keywords highlight these topics' importance in the research discourse during this period, signifying their relevance and potential impact on various aspects such as financial markets, risk management, and policy considerations.

4.5. Bibliography Coupling

Bibliography coupling serves as a comprehensive approach for analyzing the results obtained from the automated processing of a vast collection of scientific studies, utilizing a rigorously defined criterion of coupling [83]. This methodology enables categorizing studies into groups that strongly adhere to a specific criterion of interrelation. Subsequently, through a meticulous examination of the studies within these groups, a significant degree of logical correlation among them becomes evident [83]. The importance of this methodology lies in its capacity to uncover and elucidate the underlying logical connections and associations within the scientific literature, facilitating a deeper understanding of the interdependencies and coherence within the field of study.

Furthermore, bibliography coupling analysis, facilitated by tools like VOSviewer or Bibliometrix, plays a crucial role in uncovering the underlying connections and themes within the scholarly literature. It supports researchers in navigating the vast amount of information, discovering relevant research areas, and gaining insights that can inform their research endeavors and contribute to advancing knowledge in the field [84].

4.5.1. Co-Citation Analysis of the Studies

As outlined by [11], co-citation analysis is a bibliometric network analysis method used to explore the intellectual structure within scholarly research domains. It examines

the frequency of co-citation, where two authors are cited together in a set of citing studies, providing valuable insights into their perceived connection or affinity [62]. Social network analysis is a valuable tool for researchers to visualize and comprehend intricate relationships, including co-citation and cross-citation structures. In the context of incorporating green bonds into portfolio investments analysis, a co-citation network analysis was performed to unveil the latent connections among pivotal studies, thereby informing future research endeavors [85].

Utilizing the interlinked citation relationships, co-citation analysis endeavors to unveil patterns of association that depict the concealed community focused on incorporating green bonds into portfolio investments analysis. This approach sheds light on the field's literature concentration by leveraging citations as evidence. By visualizing the research network, researchers can identify key studies within the focal network and elucidate their networking relationships, offering valuable insights for future research directions [85]. Figure 15 shows the co-citation network by studies.

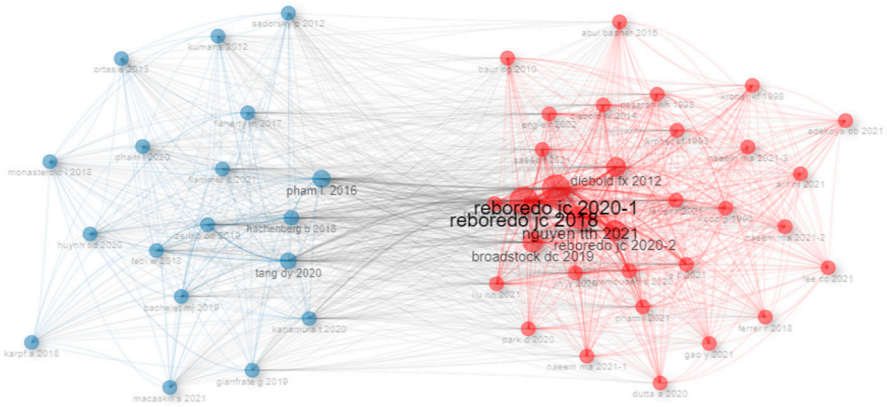


Figure 15. Co-citation Network by studies. Source: Authors' own research using Bibliometrix tool, as well as Scopus and WoS databases.

Two main clusters of studies from the co-citation network by study analysis among 50 studies were identified. First, the results of the co-citation analysis in the red node (32 studies) were visualized into a networking structure to profile the intellectual structure of incorporating green bonds into portfolio investments research. As shown in Figure 15, the label of nodes contains the first author's last name, the co-authors' initials, and the publication year. For example, the most cited study was [41] and published in 2018 was labeled as "reboredojc2018". Each line indicates that at least one follow-up study has co-cited two linked studies. The second most cited study in the red node is [73], followed by [48]. On the other hand, the co-citation analysis in the blue node, which includes 18 studies, depicts that the most cited study is [86], followed by [75,87].

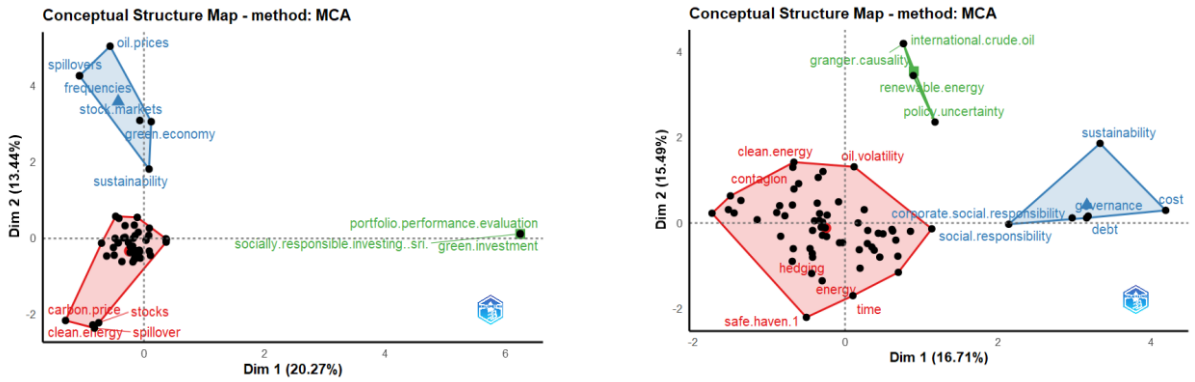
Then, the studies identified in the red node ([41,48,73]) emphasize the connection, price relationships, and network connectedness between green bonds and different financial markets. The implications of these findings are significant for portfolio management decisions, risk mitigation strategies, and the allocation of funds toward environmentally sustainable investments. The research contributes to the evolving field of portfolio theory by incorporating the unique characteristics of green bonds and their impact on portfolio diversification and risk management practices.

Additionally, the studies identified in the blue node ([75,86,87]) contribute to portfolio theory by offering empirical evidence and insights into the behavior, pricing, and impact of green bonds on financial markets. They inform portfolio managers and investors about the benefits and implications of incorporating green bonds into investment portfolios, supporting the growth of sustainable investments, and aiding in risk management and asset pricing decisions.

4.5.2. Factorial Analysis

Factorial analysis is a powerful method that plays a crucial role in incorporating green bonds into portfolio analysis by facilitating the identification of research clusters, promoting the systematic recognition of current research patterns, and providing researchers with a basis for proposing future research directions [88]. Classifying the author's keywords into different categories based on their thematic relevance is important. By organizing the keywords into distinct classifications, researchers gain valuable insights into the main focus areas within the domain of incorporating green bonds into portfolio analysis.

In Figure 16, we present the application of factorial analysis using multi-correspondence analysis. The analysis focuses on the keywords of the research records, employing automatic clustering and a maximum of 50 terms. The primary objective is to describe the variability among the correlated keywords while potentially reducing the number of unobserved keywords, thus identifying independent latent keywords. The factorial analysis results in three distinct classifications of keywords, encompassing both author's keywords and KeyWords Plus. In the author's keywords case, as shown in Figure 16a, the blue classification represents keywords such as oil prices, spillovers, frequencies, stock markets, green economy, and sustainability. These keywords provide a comprehensive overview of the broader themes and concepts related to incorporating green bonds into portfolio analysis. The red classification comprises more specific keywords like carbon price, clean energy, stocks, and spillovers. These keywords delve deeper into particular aspects of the research topic, offering a more focused perspective on relevant subtopics and factors influencing the incorporation of green bonds into portfolios. Lastly, the green classification involves keywords such as portfolio performance evaluation, socially responsible investing, and green investment. These keywords shed light on the evaluation metrics, investment strategies, and sustainability considerations associated with incorporating green bonds into portfolio analysis.



(**a**) (**b**)

Figure 16. Factorial analysis—conceptual structure map: (**a**) Author's keywords and (**b**) KeyWords Plus. Source: Authors' own research using Bibliometrix tool, as well as Scopus and WoS databases.

Similarly, for KeyWords Plus (Figure 16b), the blue classification includes keywords such as sustainability, corporate social responsibility, social responsibility, governance, debt, and cost. These keywords highlight broader concepts and themes related to sustainable practices, responsible corporate behavior, and the financial implications associated with incorporating green bonds into portfolio analysis. They provide a foundational understanding of this field's overarching principles and considerations. The red classification comprises more specific keywords like international crude oil, Granger causality, renewable energy, and policy uncertainty.

These terms delve into more specialized research aspects, focusing on analyzing factors such as energy markets, causal relationships, renewable energy sources, and the impact of policy decisions on incorporating green bonds into portfolios. The red classification enables

researchers to explore nuanced and specific areas of investigation within the broader context of green bond analysis. Lastly, the green classification encompasses keywords like clean energy, oil volatility, contagion, hedging, energy, and safe haven. These keywords shed light on topics related to clean energy investments, market volatility, risk management strategies, and the role of energy-related factors in portfolio analysis. The green classification directs attention toward key aspects that require further exploration and understanding within the domain of incorporating green bonds into portfolio analysis.

These classifications provide valuable insights into the prominent keyword categories within the domain of incorporating green bonds into portfolio analysis. The diverse range of keywords reflects the multifaceted nature of research in this field, covering areas such as sustainability, market dynamics, financial indicators, and investment strategies. By understanding the distinct keyword classifications, researchers can better understand the key focus areas and emerging trends within the research domain.

4.5.3. Historiographic Map

The historiographic map, introduced by [89], is a graphical representation of a chronological network map that captures the most significant direct citations derived from a bibliographic collection. This approach produces a network matrix that reflects the chronological connections among cited works, providing valuable insights into the historical evolution of the field. The resulting matrix serves as a foundation for analyzing the temporal dynamics of scholarly influence and the interrelationships between seminal works in the field, as outlined in [36].

According to [90], historiography maps show the chronology of primary studies citing other primary studies, thus tracing how ideas move from study to study. Just one cluster is founded in our analysis (Figure 17). Specifically, the chronology of the historiographic map begins with [76], which emerges as the earliest study relating to green bonds and the composition of investment portfolios. In [76], a structural model for green bonds is developed to explain their price formation and dynamics and address the 'greenium' phenomenon, which refers to the yield difference between conventional and green bonds with similar characteristics. The model examines the determinants of green bond value, their impact on issuer credit quality, and whether they offer cost-effective funding for sustainable investments.

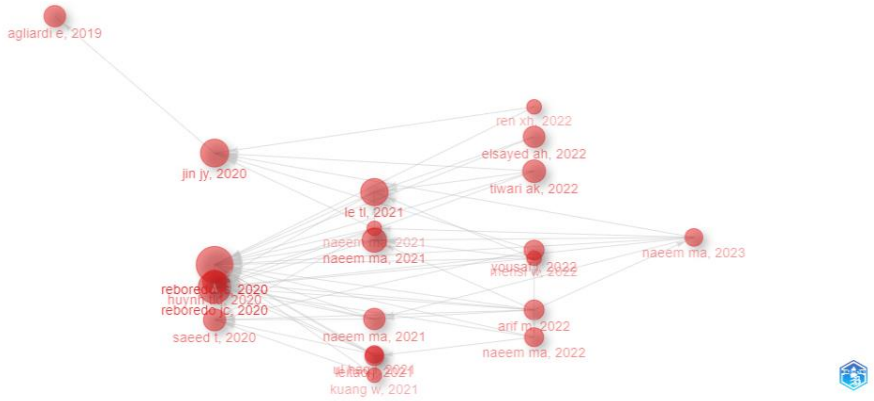


Figure 17. Historiographic map. Source: Authors' own research using Bibliometrix tool, as well as Scopus and WoS databases.

Additionally, the study explores the influence of investors' environmental concerns on portfolio allocation. The findings of [76] have important policy implications, indicating that improving credit quality can lead to lower capital costs for green bond issuers. Moreover, government tax incentives and increased investor awareness of sustainability are crucial factors in scaling up the green bonds market.

Then, ref. [76] constitutes a base that underscores the practical implications, demonstrating how improvements in credit quality, governmental policies, and investor awareness

can drive green bonds' growth and mainstream adoption, ultimately fostering sustainable investments and a transition to a more environmentally friendly economy.

Furthermore, in Figure 17, among the big topic (red node), the first subtopic that emerges is in line with hedging strategies ([26,49,51,52,91–93]). For instance, ref. [92] focuses on the hedging ability of clean energy stocks and green bonds against dirty energy assets and the portfolio implications. This study fills the research gap in understanding the relationships between clean/green and dirty energy assets by analyzing the hedging effectiveness and identifying the drivers of the hedge portfolio returns. The findings highlight the superior hedging performance of clean energy stocks, especially for crude oil, and suggest the importance of dynamic hedging strategies. This research contributes to portfolio diversification theory and provides practical implications for investors in managing economic policy risk. Thus, collectively, these studies contribute to the evolution of portfolio theory by exploring the role of green bonds and other assets in hedging, safe-haven, and portfolio diversification strategies. The findings offer valuable insights for investors, policymakers, and researchers interested in sustainable finance, risk management, and the interconnections between different financial assets in various market conditions.

Another subtheme that emerges within the red cluster in Figure 17 is connectedness and spillovers between green bonds and other financial assets [48,54,58,68,73,74,94]. These studies contribute to understanding the relationship between green bonds and various financial markets, providing insights into portfolio design, risk management, diversification, and the role of green bonds in sustainable finance. For example, the findings of [54] suggest that diversification opportunities are more evident in the short run, while long-term integration is observed between green bonds and financial markets. The direction and magnitude of spillovers vary across markets, with the world stock market being a net spillover transmitter and the corporate bond market a net receiver. Green bonds receive more volatility but transmit less in the analyzed period, and the dynamic connectedness between green bonds and financial markets is volatile over time.

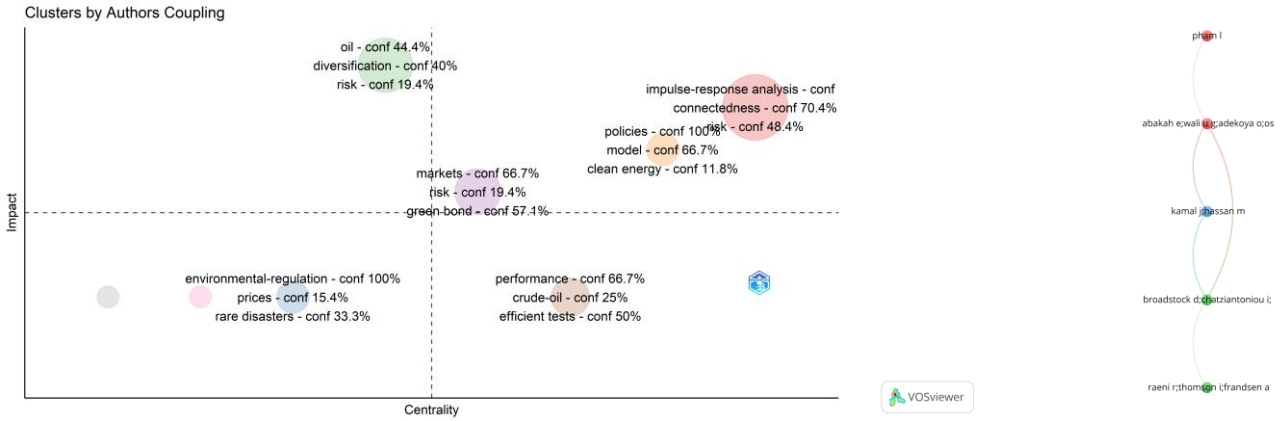
Another subtheme within the red cluster in Figure 17 combines the analysis of hedging and co-movements between green bonds and other financial assets [46,95]. For example, ref. [95] points out that green bonds are found to be effective hedges against natural gas, certain industrial metals, and agricultural commodities during periods of high volatility.

Finally, the subtheme that emerges within the red cluster in Figure 17 is related to the connection between green bonds and clean energy stocks [55,96–98]. These studies collectively emphasize the significance of incorporating green bonds, clean energy stocks, and sustainable investments in portfolio theory. They provide insights into the diversification benefits, risk reduction capacity, volatility connectedness, and safe haven characteristics of green investments. They offer practical implications for investors, portfolio managers, and policymakers seeking to build sustainable and resilient portfolios. For example, ref. [98] contributes to understanding the role of green investments in portfolio risk management and emphasizes their potential as essential components of diversified portfolios.

4.5.4. Bibliographic Coupling Analysis of Authors

Bibliographic coupling occurs when two studies exhibit a common set of references, indicating a scholarly connection between them based on the sources they cite [83]. Bibliographic coupling by authors reflects the degree of relatedness and shared information between the two studies, providing insights into their thematic similarity and potential interdependencies [99]. By identifying bibliographic coupling, researchers can uncover valuable connections and establish relationships among scholarly works, contributing to exploring and advancing knowledge within a specific field or research area.

Figure 18 shows the bibliometric coupling of authors realized in Bibliometrix (Figure 18a) and VOSviewer (Figure 18b), where the analysis is carried out for the authors who have published the studies in the field of incorporating green bonds into portfolio investments between the year 2016 and 2023.



(**a**) (**b**)

Figure 18. Bibliographic coupling by authors: (**a**) Bibliometrix and (**b**) VOSviewer. Source: Authors' research using VOSviewer, Bibliometrix tools, Scopus, and WoS databases.

In Figure 18a, the number of local citation scores quantified the authors' effect. Six clusters were created depending on the topic's significance, each with a distinct color scheme: red, orange, purple, green, pink, and blue. For this analysis, we analyzed the clusters with high centrality and impact, meaning that we just analyzed the red, orange, and purple clusters. Among these, the red cluster has a centrality of 3.05, an impact of 1.93, and 19 authors, and contains an impulse-response analysis, connectedness, and risk.

The authors in the red cluster (Figure 18a) include Elsayed et al. [54], Naeem, Conlon, and Cotter [68], Tiwari [52], Le, Abakah, and Tiwari [74], Mensi et al. [94], and others. These studies collectively contribute to the understanding of portfolio management by examining the interdependencies, diversification benefits, risk transmission mechanisms, and hedging properties associated with green bonds and their relationship with other financial assets. For example, [94] explores the dynamic and frequency of spillovers between global green bonds, WTI oil, and G7 stock markets. By employing the time-frequency spillover index and wavelet coherency approach, the study examines the dynamic nature of spillovers and the co-movements between markets. The findings reveal the crisis sensitivity of spillovers and the potential for reducing spillover size by including green bonds and oil futures in stock portfolios during turmoil periods. The study identifies net transmitters and recipients of spillovers across different time horizons and highlights the diversification benefits and hedge effectiveness of green bonds and oil in various time frames.

The orange cluster, as shown in Figure 18a, with a centrality of 2.66, an impact of 1.87, and two authors, contains the topics of policies, models, and clean energy. The studies in this cluster include the authors Reboredo [41] and Reboredo and Ugolini [73]. Then, the analysis of [73] utilizes a structural vector autoregressive (VAR) model that captures both the direct and indirect transmission of financial shocks across markets, providing insights into the interdependencies and spillover effects. Also, it employs heteroskedasticity to identify the model parameters. The empirical findings highlight the close linkage between the green bond market, fixed-income market, and currency market, with significant price spillovers from these markets to the green bond market and negligible reverse effects. In contrast, the study reveals a weak connection between the green bond market and the stock market, energy market, and high-yield corporate bond market. These findings have implications for portfolio diversification and risk management decisions, as they indicate that environmentally aware investors holding positions in green bonds should pay closer attention to fixed-income and currency markets to manage their portfolios and mitigate risks effectively.

Finally, the purple cluster (Figure 18a), with a centrality of 1.90 and an impact of 1.824, contains five authors and the topics of markets, risk, and green bonds. The studies in this cluster are conducted mainly by Yousaf, Suleman, and Demirer [98], Cepni et al. [56],

and Pham [75]. Then, for example, the findings of [98] emphasize the value of incorporating green investments, mainly green bonds, into portfolio strategies to diversify, hedge, and enhance risk-adjusted returns, especially during turbulent market states induced by significant events like the COVID-19 pandemic.

The Figure 18b, with at least two studies published in the journal as a criterion, offers a visual representation that identifies the leading authors on the analyzed topic, yielding 99 authors from a total of 247 authors; it includes five items and three clusters: red, blue, and green. The red cluster includes the authors Pham [75], Abakah [29], and Abakah et al. [69]. Then, for example, the study by [69] examined the dynamic price correlation and connectedness between the blockchain market and green (eco-friendly) financial assets. With the rise of blockchain technology, digital assets such as cryptocurrencies, DeFi (Decentralized Finance), and NFTs (Non-Fungible Tokens) have garnered substantial attention from investors and policymakers. However, it is crucial to understand the potential negative environmental implications of the blockchain market and how they can affect eco-friendly financial assets. The findings in [69] shed light on the correlation and connectedness between the blockchain market and green financial assets. Understanding these dynamics is crucial for portfolio analysis and risk management, as it provides insights into the potential transmission of shocks from the blockchain market to eco-friendly investments. Policymakers and investors can leverage these findings to make informed decisions regarding integrating blockchain assets and their potential risks to environmentally conscious portfolios.

Additionally, the blue cluster in Figure 18b includes the following two authors: Kamal and Hassan [100]. For instance, [100] aimed to analyze the influence of the cryptocurrency environment attention index (ICEA) on clean energy stocks and green bonds, utilizing Ordinary Least Squares (OLS), quantile regression, quantile connectedness approach, and the Dynamic Conditional Correlations (DCC)-GJR-GARCH model. These methodologies allow for comprehensive data analysis and provide insights into the interplay between the ICEA, clean energy stocks, and green bonds. The findings in [100] have important implications for investors seeking to construct optimal portfolios with carbon-free assets across different market states. The study highlights the potential benefits of including clean energy stocks and green bonds in portfolios as diversification tools against the ICEA during bearish market conditions. However, it also emphasizes the need to consider the relationship between the ICEA and green bonds, as their correlation may vary over time. These insights can guide investors in making informed decisions when constructing portfolios with environmentally friendly assets.

Finally, the green cluster in Figure 18b involves the authors Broadstock, Chatziantoniou, and Gabauer [11] and Raeni, Thomson, and Frandsen [101]. Then, [11,101] contributed to the evolution of portfolio theory by examining the role of green bonds in investment portfolios and their connection to sustainable development goals. The authors in [11] examined the impact of green bonds on portfolio efficiency and risk, while [101] explored the integration of green bonds into sovereign bond portfolios to address climate change concerns. These studies shed light on the importance of incorporating environmentally responsible financial instruments within portfolio management strategies and their potential benefits regarding risk-adjusted returns and sustainable development.

5. Discussion

Literature reviews conducted in the field of green bonds offer a comprehensive understanding of their impact on the financial market. These studies highlight the importance of various factors such as issuer quality, policy effectiveness, sustainability, and transparency in price determination, as well as investor confidence in this sector. These studies provide valuable information about the green bond market and its impact on sustainable development. The review by [102] emphasized the need to assess the effectiveness of green bonds in driving sustainable projects beyond bond issuance. This suggests that attention

should not only be focused on the volume of green bonds issued but also on their impact in promoting renewable energy and energy efficiency measures.

Furthermore, the study on the existence of a green premium conducted by [103] confirms the presence of a price premium for green bonds, especially those issued by governments with well-defined governance procedures and information on green bonds. This finding reinforces the notion that investors are willing to pay higher prices for bonds with strong environmental attributes, highlighting the importance of sustainability considerations in their determination [104]. In line with this, [105] also conducted a literature review on green bond markets [106] and recommended further research to explore different types of green bonds, evaluate the impact of various green projects, understand the perspectives of different market participants, and leverage advanced technology to drive the green bond market.

A bibliometric analysis by [1] demonstrated the interdisciplinary nature of studies on green bonds, highlighting collaboration efforts across diverse disciplines. This reflects the global significance of green bonds as a financing tool for sustainable development. Consequently, ref. [107] emphasized the challenges associated with green project financing and called for research to investigate the direct relationship between green bonds and sustainable development. Understanding the environmental and social benefits of green bonds is crucial for assessing their overall impact, which is also addressed in [14], and for classifying the existing literature on green bonds into different groups to provide a comprehensive understanding of green bonds and their implications.

Additionally, the analysis conducted by [106] underscores the importance of incorporating environmental, social, and governance (ESG) criteria in environmentally responsible investments, with green bonds being recognized as a key instrument to achieve this goal. On the other hand, ref. [14] explores the diversification and coverage benefits of including green bonds in portfolios during the COVID-19 pandemic. Likewise, the review of [108] highlights the role of external reviews in the secondary market of green bonds, influencing investor confidence and perceived credibility. This underscores the need for transparency and high-quality information in the green bond market.

Compared to the literature reviews, this research examines recent trends and new investigations on integrating green bonds from the perspective of portfolio investment, an approach not addressed in the identified literature analyses. This study presents a novel approach using the Tree of Science (ToS), VOSviewer, and Bibliometrix to investigate the integration of green bonds in portfolio investments. The findings contribute to understanding current trends in this field and lay the groundwork for future research. Additionally, strategies are proposed for data collection and expanding the boundaries of knowledge in analyzing green bond integration into portfolio investments. The aim is to provide valuable insights to market participants, researchers, policymakers, and decision-makers, facilitating informed decision making.

6. Conclusions

This scientific study presents a comprehensive scientometric analysis that explores the current state of the art regarding integrating green bonds into portfolio investments. Utilizing various analytical techniques, including examination of authors and sources, analysis of studies, and bibliography coupling, we aim to uncover the existing frontiers of research in this field, focusing on recent trends and avenues for further investigation. Specifically, we analyze the configuration of research conducted on this topic from 2016 to June 2023, incorporating and analyzing a total of 102 studies sourced from the Scopus and Web of Science databases.

To conduct this analysis, we employ advanced scientometric tools such as the Tree of Science (ToS), VOSviewer, and Bibliometrix to provide a comprehensive overview of the research landscape and contribute to a better understanding of the progress made in the integration of green bonds into portfolio investments.

The results highlight that one of the most explored topics is the interconnectedness and volatility spillovers between green bonds and different types of financial assets, including not only conventional assets such as stocks, bonds, and commodities but also more current assets such as cryptocurrencies, DeFi (decentralized finance), and NFTs (non-fungible tokens). The results are diverse and identify the potentialities of green bonds regarding portfolio diversification and hedging strategies. Further research on this topic should adopt more robust methods, such as machine learning analysis, to deeply study the co-movements among green bonds and different financial assets and their influence on portfolio investments.

Additionally, investigating green bonds' pricing dynamics and market efficiency and their interaction with other asset classes is an area ripe for further exploration. Thus, understanding the drivers of green bond prices, including factors that influence their risk premiums and their correlation with other financial instruments, can enhance understanding of their role in diversified portfolios and their potential for risk management and return enhancement.

Furthermore, another significant theme that emerges from the analysis of incorporating green bonds into portfolio investments is the exploration of risk management strategies and the impact of policy uncertainty. Understanding and effectively managing the risks associated with green bonds is crucial for investors seeking to incorporate these sustainable financial instruments into their portfolios. Furthermore, green bonds are influenced by government policies, regulations, and incentives aimed at promoting sustainable development and mitigating climate change. Changes in these policies can significantly impact the value and performance of green bonds, introducing additional uncertainties for investors. Consequently, researchers explore the implications of policy shifts and uncertainties on the risk and return characteristics of portfolios containing green bonds.

Finally, the exploration of incorporating green bonds into portfolio investments has revealed another important theme: the growing recognition and emphasis on sustainability and social–environmental considerations. This theme reflects a notable shift toward environmentally responsible investing and the re-composition of investment portfolios to incorporate green bonds and other asset classes that finance social activities, with social bonds playing a crucial role.

6.1. Policy Recommendations

Although the global green bond market continues to expand, there remains a need for additional public policy instruments to incentivize issuance at the small and medium enterprise level. By implementing such measures, portfolio investors will gain broader market opportunities to integrate these environmentally focused instruments into their portfolios. This strategic approach enables investors to effectively manage risks, diversify portfolios, and contribute to achieving the environmental objectives set by SDGs.

6.2. Further Scope

Considering the research trends and findings, conducting further studies on topics related to green bonds in portfolio investments will facilitate the improvement of financial practices. From both practical and scholarly standpoints, additional research could be undertaken to develop an investment framework that includes ESG in the core. In this way, further research may include:

- Examining how integrating sustainability factors, such as environmental, social, and governance (ESG), into portfolio investments alongside traditional financial metrics can optimize portfolio performance.
- A deeper analysis of this area could include the examination of dynamic hedging strategies that can incorporate a time-varying approach, including uncertainty.
- Analyzing the effectiveness of various ESG integration techniques and their impact on portfolio risk and return is essential for portfolio managers and investors seeking to align their investment strategies with sustainability goals.

- Assessing the green bonds' portfolio composition in emerging markets.

The findings of these studies will allow advancing the green bonds and portfolio theory literature. Incorporating green bonds into portfolio investments should focus on integrating sustainability factors in portfolio construction, the role of social bonds, impact measurement methodologies, pricing dynamics, and the regulatory environment. Thus, by addressing these research avenues, scholars can contribute to advancing portfolio theory and provide practitioners with valuable insights to navigate the evolving landscape of sustainable and socially responsible investing.

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