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Decoding the Dynamics of Voluntary Carbon Markets: A Scientometric Analysis of Two Decades of Research and Development

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ABSTRACT. This study aims to synthesize Voluntary Carbon Market (VCM) research from 2002 to 2023 using the Web of Science database and the scientometric tool, CiteSpace. Despite the 73 publications uncovered, with an average citation rate of 16.84 per publication and an h-index of 19, the field still faces significant challenges. While these metrics reflect a solid citation impact and a well-connected research network, the analysis reveals a lack of real-world application in VCM studies. Although international cooperation is emphasized as crucial for the field's advancement, current research remains largely theoretical. This gap highlights the need for future studies to move beyond conceptual discussions and focus on practical, scalable solutions. For VCM to have a meaningful impact, it must integrate emerging regulations and technologies that can benefit multiple stakeholders. Research should explore applications in local microgrids and residential sectors, aligning with energy trends and meeting both consumer demand and environmental goals. Without this shift towards actionable insights, the potential of VCM to drive sustainable change will remain underutilized.

Key words: Voluntary Carbon Market, Scientometric Analysis, CiteSpace

INTRODUCTION

Voluntary Carbon Market operates independently from compliance markets, enabling businesses, governments, NGOs, and individuals to offset emissions by purchasing carbon offsets (Spilker & Nugent, 2022). Unlike regulated markets, the VCM lacks formal rules, fostering experimentation in methods, technologies, and procedures potentially adaptable in regulatory contexts. This flexibility often results in lower transaction costs, promoting innovation (Kollmuss et al., 2008).

VCM plays a vital role in funding carbon protection programs, offering financial incentives for conservation and restoration projects. These projects create carbon credits, reflecting reduced or avoided greenhouse gas emissions, which are sold to offset carbon footprints, thus supporting ecosystem conservation (Dencer-Brown, 2022; Oldfield, 2022; Atmadja et al., 2022). However, the economic valuation of carbon storage remains under-recognized (Armstrong et al., 2019), and there's a risk of climate injustice as resource-limited countries might bear

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disproportionate burdens of industrialized nations' climate policies (Van Dam et al., 2021).

Initially, public institutions like the World Bank drove the VCM's demand, but future trends suggest a shift towards private sector engagement, influenced by increasing net zero commitments (Kreibich & Hermwille, 2021). Several comprehensive reviews have collectively addressed vital concerns within the VCM field, encompassing historical, infrastructural, and market evolution aspects, with a particular focus on derivatives (Spilker & Nugent, 2022), implications of scaling up Carbon Dioxide Removal (CDR) (Ghaleigh & Macinante, 2023), and quantification of food Carbon Footprints (CFs) (Cammarata et al., 2023). While insightful, these reviews often narrowly concentrate on specific areas, a constraint linked to the extensive labor involved in synthesizing vast literature.

To overcome this limitation, this study employs Scientometrics, a quantitative approach for scientific evaluation, previously applied in thermal tolerance, aquaculture, and solar energy research (Azra et al., 2022; Iqbal et al., 2022; Mohd Noor et al., 2023). This method incorporates a range of techniques, from descriptive statistics to network analysis and machine learning. Utilizing the Web of Science database and CiteSpace, this study aims to synthesize EMS research from 2002 to 2023, exploring publication trends and central topics. This research seeks to answer the twol key questions: ((i) What are the overall publication trends in terms of output? and (ii) What are the central topics/clusters?

METHODOLOGY

Scientometric Approach

This study adopts a scientometric approach to analyze articles on Voluntary Carbon Market published in the Web of Science (WoS) database from 2002 to 2023.

DATABASE SEARCHES

Data collection utilized the WoS core collection, a comprehensive source for scholarly information. The search targeted titles, abstracts, keywords, author names, and Keywords Plus. The search phrase was "TS=("Voluntary Carbon Market*")", using an asterisk for variations. The focus was on original research articles, excluding commentaries, short communications, books, chapters, protocol papers, theory/discussion papers, and editorials. The search was conducted on December 12th, 2023.

DATA ANALYSIS

Data analysis comprises two parts: Descriptive and Scientometric Analysis.

1. Descriptive Analysis: This phase involved analyzing the number of papers published annually, the journals where they appeared, and the most productive institutions, and countries.

2. Scientometric Analysis: Utilizing CiteSpace 6 version 6.2 for Windows, this part included:

a. Dual-Map Overlay Analysis: This categorized literature into cited and citing journals, representing journal positioning and connections. It visualized the frequency of citations between journals, with the map's left side displaying EMS-focused journals and the right side showing cited journals.

b. Document Co-citation Analysis (DCA): DCA examined co-citations in individual and clustered articles. Key metrics included burstness (spikes in citations), centrality (influence in the network), and sigma (combination of centrality and burstness indicating novelty). Cluster analysis employed the Log-Likelihood Ratio (LLR) method for labeling, with a timeline view and cluster view for network visualization. The study assessed cluster quality using the Modularity Q index and Silhouette Metric.

The methodology's flowchart (Figure 1) summarizes these steps, providing a visual guide to the research process.

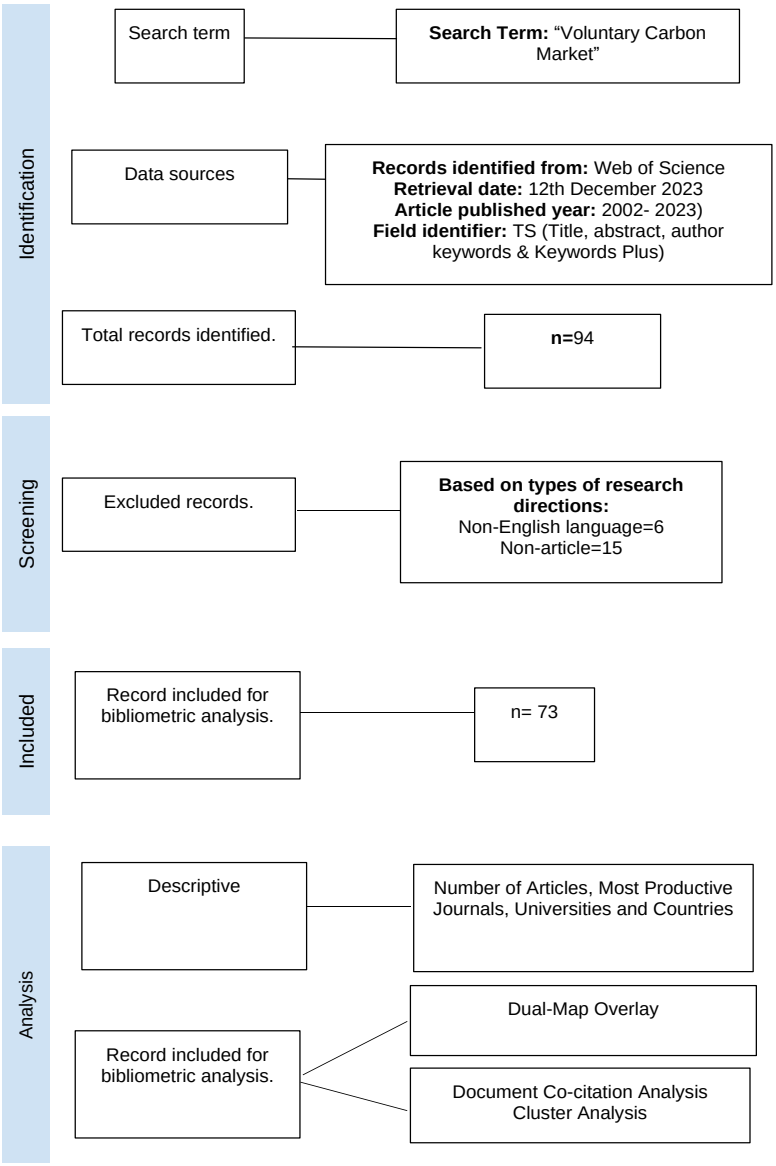

Figure 1. Methodology's flowchart of the research.

RESULTS

Descriptive

The research on the Voluntary Carbon Market (VCM) has yielded a total of 73 publications, boasting an h-index of 19. These works collectively have received 1,229 citations, averaging 16.84 citations per publication. A visual representation of this data, shown in Figure 2, illustrates a rising trajectory in VCM research from 2002 to 2023. This upward trend highlights an increasing focus and growth in VCM-related publications. Notably, the annual number of publications consistently remained below 10 before 2021. However, there was a marked increase in 2021, followed by a continued rise, culminating in 12 publications in 2022, as detailed in Figure 2.

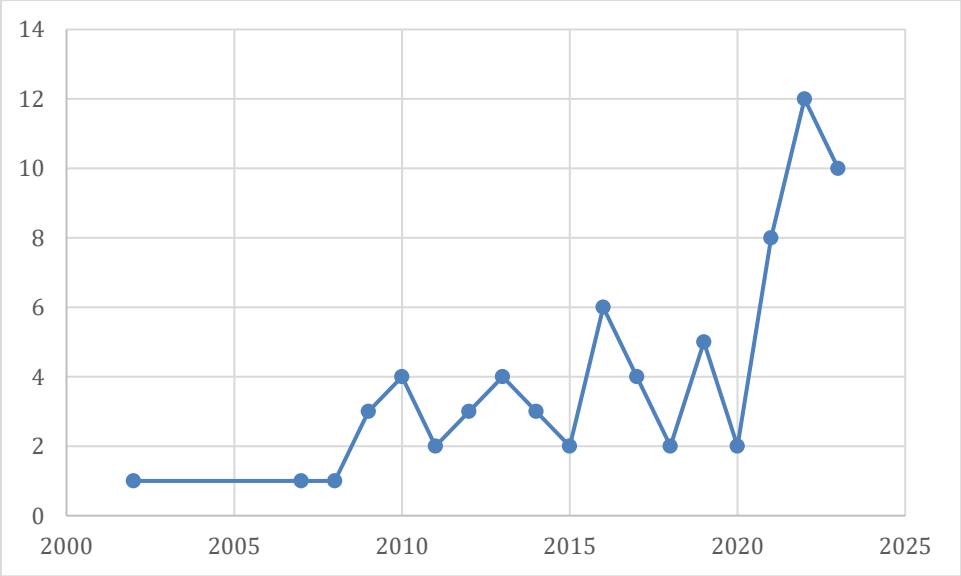

Figure 2. Number of research articles regarding Voluntary Carbon Market published annually since 2002.

Figure 3 provides a summary of the contributions by different countries to the field of Voluntary Carbon Market research. The United States leads with 17 records, followed by England with 11, and Germany with 10. Australia and Scotland each have 7 publications, while the People's Republic of China has contributed 6. Canada and the Netherlands have each produced 5 records. This distribution indicates a broad international engagement in VCM research, with the highest contributions coming from the USA, England, and Germany.

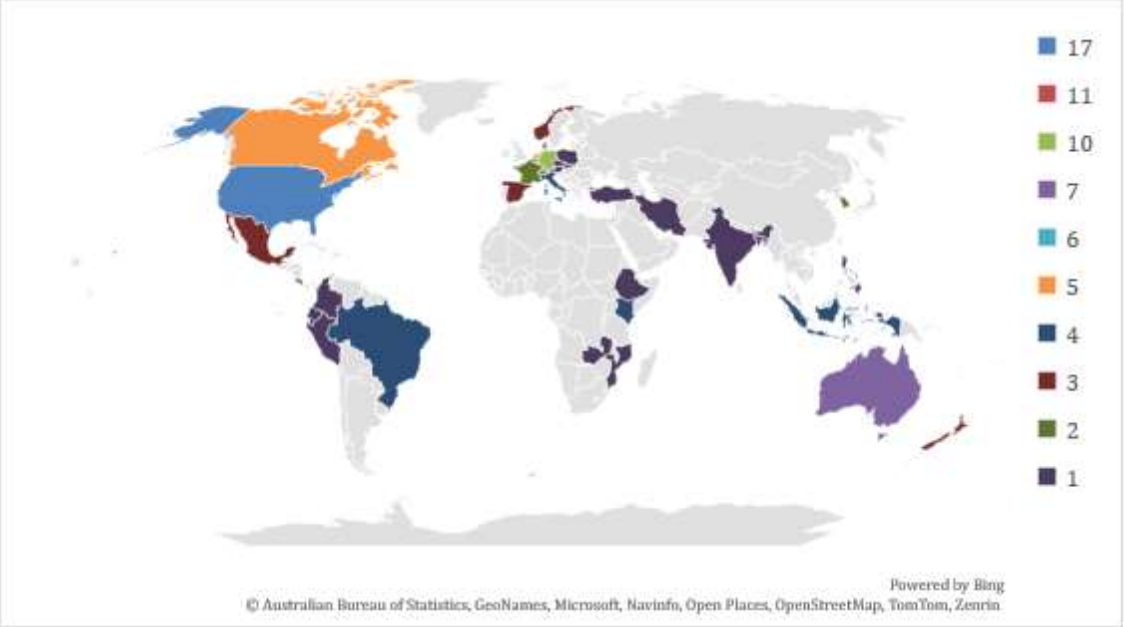

Figure 3. Summary of the contributions by different countries to the field of Voluntary Carbon Market research

The table presents a ranking of journals by their contribution to research on the Voluntary Carbon Market. At the forefront are 'Carbon Management' and 'Climate Policy', each with four published articles. Following closely are 'Ecological Economics', 'Forest Policy and Economics', and 'Forests', each with three articles to their credit. Further contributing to the field are 'Ecosystem Services', 'Environmental and Planning Law Journal', 'Forest Ecology and Management', 'Journal of Environmental Management', and 'Marine Policy', each with two published pieces. These journals represent the primary outlets for scholarly communication and discourse in the realm of Voluntary Carbon Market research.

Table 1. Number of publications from the top ten journals containing research about Voluntary Carbon Market published between 2002 and 2023.

Publication Titles	Record Count
Carbon Management	4
Climate Policy	4
Ecological Economics	3
Forest Policy and Economics	3
Forests	3
Ecosystem Services	2
Environmental and Planning Law Journal	2
Forest Ecology and Management	2
Journal of Environmental Management	2
Marine Policy	2

SCIENTOMETRIC

The scientometric analysis provided a detailed examination of the intellectual landscape within Energy Management Systems (EMS) research, covering works published between 2002 and 2023. Utilizing methodologies such as dual-map overlay and document co-citation analysis (DCA), the study traced the evolution and progression of EMS as a distinct research area. The analysis revealed a robust network characterized by 442 nodes and 1,283 links, with a network density of 0.0132, highlighting the breadth and intricate connections that define the collaborative nature of EMS research.

Dual-map Overlay

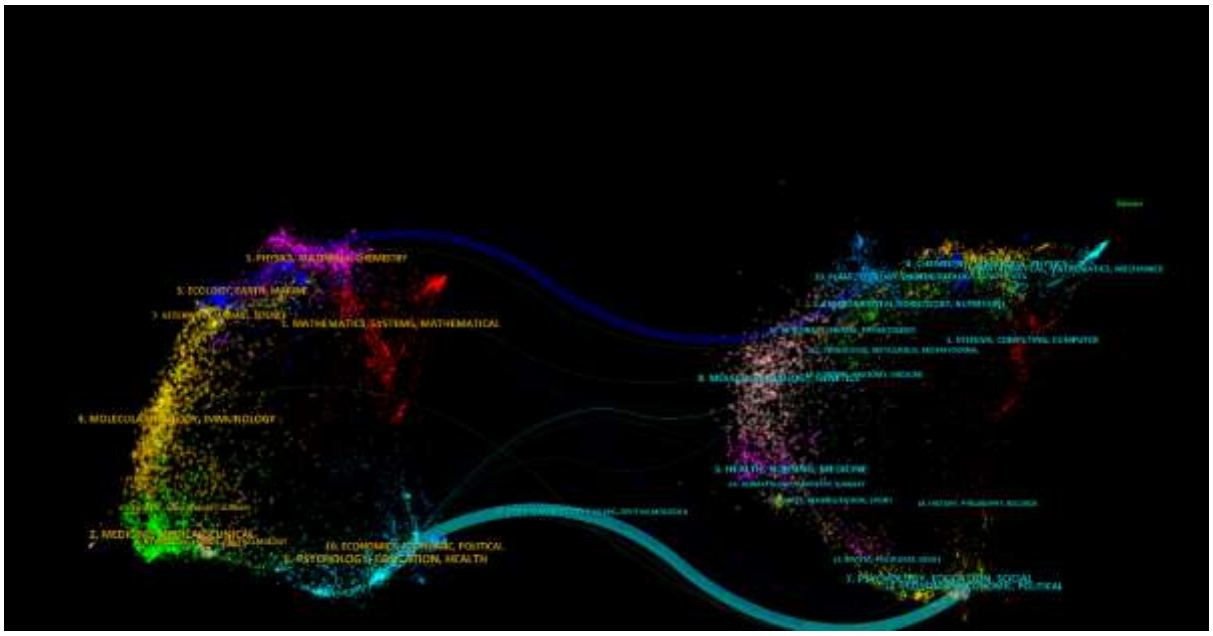

Figure 4. Dual map overlay on Voluntary Carbon Market. Points represent literature, ellipses represent groups of subject matter, and directional lines represent connection between subjects. Each unique discipline is represented by a different colour.

The dual-map overlay depicted in the figure illustrates the landscape of scholarly activity within the Voluntary Carbon Market (VCM) research. On the left, we observe the distribution of journals that have been citing VCM work, with clusters highlighting varied disciplines such as "Ecology, Earth, Marine," "Physics, Materials, Chemistry," and "Molecular Biology, Immunology." Conversely, the right side of the map delineates the fields from which these citing journals draw their references, with discernible clusters like "Environmental, Toxicology, Nutrition" and "Chemistry, Materials, Physics." Curved lines traverse the expanse between these two realms, varying in thickness, and denote the citation traffic from one discipline to another.

DOCUMENT CO-CITATION ANALYSIS

The Document Co-citation Analysis (DCA) network for VCM research showcases a highly structured and cohesive configuration, as indicated by the provided modularity and silhouette metrics. With a Modularity Q Index of 0.9461, the network demonstrates a profound modular construction, suggesting the presence of distinct clusters that are densely interconnected within themselves but sparsely connected with one another. Such a high modularity is indicative of mature subfields or specialized topics within the EMS research domain, each representing a concentrated area of scholarly focus.

Complementing this, the Weighted Mean Silhouette score of 0.9915, alongside a Harmonic Mean of 0.9683, underscores the high degree of internal consistency and separation between the clusters. These silhouette values signal that the documents within each cluster share strong similarities and are distinctly different from those in other clusters, affirming the network's quality and the clarity of thematic delineations. This level of clustering quality implies that the research landscape is neatly organized into well-defined topics, offering a reliable framework for academics to navigate the various research themes, their relationships, and their relevance within the broader scope of VCM research.

Table 2. *The 8 major clusters that emerged from Document Co-citation Analysis. Size represents the number of publications in a cluster, and silhouette score indicates levels of homogeneity. Labels were derived from log likelihood ratios (LLR).*

ClusterID	Size	Silhouette	Label (LLR)	Average Year
0	37	1.000	agricultural sequestration	2020
1	25	0.990	voluntary carbon-offset scheme	2008
2	24	1.000	bale mountains ethiopia	2011
3	23	1.000	new zealand	2015
9	18	0.960	fair	2011
10	17	0.977	entitlement	2018
13	10	1.000	existing soil carbon code	2020
19	8	1.000	integrating multiple benefit	2009

Table 2 outlines various clusters identified in a scientometric analysis, each representing a distinct theme within the research landscape, characterized by their size, cohesion, and temporal placement. Cluster 0, the largest with 37 documents, has a perfect silhouette score of 1, indicating strong thematic coherence. Its label "agricultural sequestration" with an LLR score of 5.37 suggests a robust focus on carbon capture in agricultural practices, emerging prominently in the year 2020. Cluster 1 comprises 25 documents and has a silhouette score of 0.99, which denotes high internal similarity among the documents. Labelled "voluntary carbon-offset scheme" with a high LLR score of 9.19, it reflects concentrated research activity in this area around the year 2008.

Cluster 2 also has a perfect silhouette score, encompassing 24 documents, indicating a focused research theme named "bale mountains ethiopia," recognized in 2011. Cluster 3, with a silhouette score of 1 and consisting of 23 documents, is labeled "new zealand," pinpointing this region's significant research contributions in 2015.

Further down, Cluster 9 has 18 documents with a silhouette score of 0.96, labeled "fair," which could indicate research into equitable aspects of carbon markets, noted in 2011. Cluster 10, with 17 documents and a silhouette score of 0.977, carries the label "entitlement," suggesting a focus on legal or rights-based aspects of carbon markets, observed more recently in 2018. Cluster 13 is a smaller group with 10 documents but has a strong silhouette score of 1, indicating cohesion in the topic "existing soil carbon code," with research concentrated in 2020. Lastly, Cluster 19, with 8 documents and a perfect silhouette, is labelled "integrating multiple benefit," highlighting a multifaceted approach to carbon market benefits, a theme that was prevalent in 2009. Each cluster represents a focused area of research within the broader domain, demonstrating the diverse and evolving nature of scholarly inquiry into carbon markets and related environmental issue

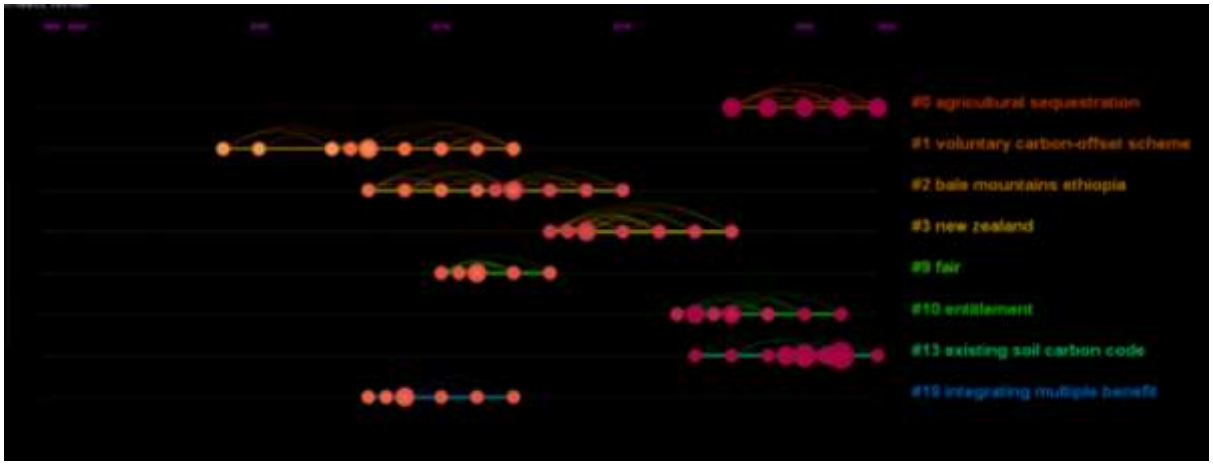

Figure 5. Summary of 8 identified document cluster lifetimes (solid lines). Cluster labels were generated from CiteSpace. Circle size corresponds to cluster size (i.e. number of publications).

DISCUSSION

This study aim is to synthesize VCM research published between 2002 and 2023 using the Web of Science database and the scientometric tool, CiteSpace. This research seeks to answer two key questions: (i) What are the overall publication trends in terms of output? And (ii) What are the central topics/clusters? We discuss our results in detail below.

(i) Publication Trends in Terms of Output: Analysis of VCM publications revealed an ascending scholarly trajectory, signaling the field's maturation over the past two decades. The h-index of 19 for the 73 publications uncovered denotes not only prolific output but also significant citation impact, demonstrating the field's scholarly influence. An average citation rate of 16.84 per publication is a testament to the sustained relevance and engagement with this body of work. The post-2021 surge in publications, as visualized in Figure 2, may reflect an adaptive response to a changing environmental policy landscape, growing recognition of VCM's role in climate strategy, or a pivot in the scientific community towards innovative sustainability solutions. Geographical contribution patterns, as summarized in Figure

3, indicate that the United States, England, and Germany are pivotal to VCM research. This distribution may mirror these nations' involvement in carbon market initiatives and their commitment to environmental research and policy development. The diversity of journals listed in Table 1, especially 'Carbon Management' and 'Climate Policy', underscores the interdisciplinary reach of VCM research, bridging the gap between ecological sustainability, law, and economic policy.

(ii) Central Topics/Clusters: The central themes, as revealed by the cluster analysis, are anchored by "agricultural sequestration," "voluntary carbon-offset scheme," and "bale mountains ethiopia." The high silhouette values for these clusters indicate tightly knit research communities with a focused agenda. The threads binding these clusters include the implementation of the Kyoto Protocol and the exploration of renewable energy integration, reflecting the growing complexity and strategic importance of VCM in global conservation efforts.

Furthermore, the role of VCM in corporate strategy warrants deeper examination, particularly as firms increasingly commit to net-zero targets. The interplay between corporate social responsibility and VCM could reveal insights into the market's function as a bridge between profit-driven entities and their broader environmental commitments. The dynamic nature of VCM research is poised for further expansion, driven by technological innovation, evolving policy frameworks, and the imperative of climate change mitigation. The robust academic interest in VCM suggests that it will remain a critical topic within sustainability and environmental economics research, with potential to profoundly influence both theoretical discourse and practical application.

CONCLUSION

This study's reliance on the Web of Science (WoS) database, while potentially introducing a selection bias, was a deliberate choice due to WoS's recognized publication standards and its extensive collection of scientific and social science research papers. Nevertheless, a comparative analysis with other databases could be insightful for future research to ensure a comprehensive coverage and to uncover any overlooked studies. Additionally, the utilization of CiteSpace for data collection, though potentially capturing some extraneous topics, offered a methodological advantage in terms of replicability and efficiency. Future studies aiming for greater precision might opt for more stringent keyword filters or a manual review of data to refine the relevance of included studies. Despite these methodological considerations, the study provides an insightful overview of the Voluntary Carbon Market (VCM) research landscape, underscoring the critical role of international collaboration in advancing the field. The intersection of technology and VCM, particularly the integration of digital solutions like blockchain, represents a promising direction for future research, potentially enhancing the transparency and efficacy of carbon trading mechanisms. Furthermore, exploring the socio-economic impacts of VCM, especially on local and indigenous communities, is essential for a more comprehensive understanding of the market's sustainability. As we look ahead, it is crucial for future investigations to extend beyond the theoretical and into the practical applications of VCM, examining how emerging technologies and policies can be harmonized to benefit diverse stakeholders. Such research could pave the way for innovations in energy management systems (EMS) that are adaptable to both microgrids and residential settings, resonating with the latest energy trends and fulfilling the dual objectives of consumer needs and

environmental stewardship.

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COMPETING INTEREST
The authors declare that there are no competing interests.

COMPLIANCE OF ETHICAL STANDARDS
Not applicable.

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