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MAPPING THE EVOLUTION OF THE CARBON CREDIT MARKET AND OFFSET SYSTEM: A BIBLIOMETRIC ASSESSMENT BASED ON SCOPUS DATA (2010-2020) USING R AND VOSVIEWER

Ayush Kumar Sharma[1], Dr Mamta Pankaj Jain[2], Dr Shikha Pareek[3], Dr Neeti Mathur[4]

[1]Assistant Professor, Department of Finance, Pune Institute of Business Management, Pune, Maharashtra. Email: asxavierian74@gmail.com, ORCID ID: 0000-0002-6837-2201
[2]Assistant Professor, Management, NIIT University, Neemrana, Rajasthan. Email ID: mamta9sep@gmail.com, ORCID ID: 0000-0003-0453-7326
[3]Assistant Professor, Department of Business Administration, JECRC University (Alwar Campus), Rajasthan. Email: shi24pareek@gmail.com
[4]Assistant Professor, Department of Management Studies, Sir Padampat Singhania University, Udaipur, Rajasthan, Email ID: neeti.mathur@spsu.ac.in , ORCID ID: 0000-0002-1888-7573

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Abstract
This study aims to develop a framework for the Carbon Credit Market. Assessment of credit risk in financing environmental performance and the voluntary market. A total of 5,432 peer-reviewed journal articles published during the years 2001 to 2026 were reviewed to map out the academic structure and evolution of this field. The study utilises bibliometric techniques such as citation network analysis, co-citation analysis, content analysis, publication trends and keyword analysis, which draw data from Scopus for analysing literature on carbon markets, environmental finance and risk assessment. The studies have been classified into three phases: the first phase is development on a foundation between 2001 and 2010, a consolidation phase from 2011 to 2018, and an acceleration phase from 2019 to 2026, where the volume of publications has seen a threefold increase. The study lays out a potentially useful foundation for future, more integrated risk pricing models that will encompass technical, behavioural, and institutional aspects to improve market transparency and environmental integrity in carbon credit pricing.

Keywords: *Carbon Markets; Carbon Credit Risk; Credibility assessment; bibliometric analysis; Citation analysis; Environmental finance; voluntary carbon markets*

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1. Introduction

The evolution of financial markets, regulatory architectures, and corporate strategies worldwide has been significantly influenced by the global recognition of climate change (Stern, 2007) (Press, 2018). The Kyoto Protocol of 1997 introduced mechanisms such as the Clean Development Mechanism (CDM), which marked the formal emergence of carbon offset programmes (Michaelowa, 2019). This subsequently set a framework for developed nations to invest in emission-reduction projects in developing nations, claim credits for these projects, and deduct them from their own domestic climate commitments (Schneider, Kollmuss, & Lazarus, 2015) (Wara, 2007) . This created the foundation that evolved into carbon credit markets. At first, these markets were compliance-driven. Later, they became voluntary markets where companies offset emissions. They do this by purchasing credits from projects that sequester or remove atmospheric carbon dioxide (Donofrio, 2021) . Carbon credit markets were conceived as market-based instruments for greenhouse gas reductions but also as successful mechanisms that align environmental objectives with economic incentives (Stavins, 2019) (Green, 2021). Markets allow firms to obtain credits for reducing or removing carbon from the atmosphere (Kollmuss, Zink, & Polycarp, 2008) (Broekhoff, 2019) . Firms can then offset emissions through investment in such projects. In theory, the framework achieves the most economically efficient emissions reductions while also encouraging investment in tools and methods to mitigate climate change worldwide (Tietenberg, 2006).

Despite the above development, the practical application of the carbon markets controversies is still rampant (Song, 2019) (Cames, 2016) Regarding the credibility and reliability of carbon credits themselves (Badgley, et al., 2022) . Critics claim that a large portion of credits traded in voluntary markets do not reflect real or permanent emissions reductions (West, et al., 2023) . Enduring inquiries into additionality, verification protocols and long-term carbon permanence have induced scepticism at all levels, including investors, regulators and environmental advocacy groups (Haya, 2023). Due to increased regulatory and public scrutiny, the robustness of underlying credits has become just as significant as the number of credits traded (Trouwloon, 2023).

From a financial analytics perspective, this credibility issue poses a new dimension that is not tackled in the literature: the systematic pricing of credibility risks (Kreibich & Hermwille, 2021) (Blaufelder, 2021) . Classic pricing frameworks for carbon credits are largely based on supply–demand equilibria, regulations and macroeconomic factors (Li, 2022) (Chevallier, 2011) . These approaches often view carbon credits as relatively homogeneous financial instruments, and it is often assumed that all verified credits have similar environmental integrity (Bumpus A. G., 2008) (Newell, 2013) .In reality, the credit quality is quite heterogeneous across different typologies of projects, with different verification and monitoring methods (Liu, 2025) (Roe S. S.-B., 2013) . This difference creates unpredictability that greatly affects market price formation and companies taking up the instruments (Kossoy, 2012) (Hamrick & Gallant, 2018).

The existence of credibility risk poses a noteworthy strategic challenge for corporate actors (Delmas, 2011) (Seele, 2017) . Carbon offsets are increasingly being put in the strategies of contemporary companies to complement a wider sustainability and emissions-reduction strategy. However, the utilisation of the offsets themselves is complicated by scrutiny over possible greenwashing (Marquis, 2016) . But corporate climate action has become a competitive priority despite standardisation on climate action classification criteria in due course. (Busch, 2022) . This signifies how important it is to consider the concept, as it has had a significant impact on market pricing and demand for offset credits (Kreibich N. H., 2022) (Cullenward, 2020). Increasingly, the scholarship in environmental finance has highlighted the need for more sophisticated approaches to the valuation of carbon credits in response to these concerns (Dornan, 2017) (Bumpus A. G., 2011). Emerging analyses contend that pricing should incorporate key risk determinants such as verification uncertainty, project length and institutional quality instead of treating all credits as commodities (Ahmad, 2024) .In theory, such approaches increase market transparency and boost incentives, resulting in genuine emission reductions (Bates, 2024) (Kollmuss A. S., 2015) . Despite growing attention to these concerns, no widely accepted framework currently integrates these risk dimensions into carbon credit pricing models. (D, Gillenwater, T, & Cage, 2019) (Macintosh, 2012).

The study aims to find answers to the following questions:

RQ1: How have the intellectual structure and thematic landscape of carbon credit and environmental finance been shaped during 2001-2026?

RQ2: What are the microscopic trends, citation trajectories, and publication dynamics in the selected area of knowledge in different phases of evolution?

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RQ3: Which core cluster, influential node and collaboration network constitute the intellectual foundation of carbon credit risk assessment in Scopus literature?
RQ4: What thematic shifts are driving the literature towards new dimensions of finance?
RQ5: How can technical, behavioural and institutional risk factors identified in the bibliometric corpus be synthesised into an operational risk-pricing model?

This study contributes to the literature by providing a systematic bibliometric analysis of carbon credit risk and pricing. Existing research on risk-adjusted pricing identifies three primary dimensions: non-permanence risk, issuance (or default) risk, and verification risk (Galik, 2009) (Kooten, Eagle, Manley, & Tanaka, 2004) .The pricing literature identifies three risk dimensions: non-permanence risk and issuance risk, Verification-related uncertainties are consistently framed in the literature as "verification risk." Building on this, the study analyses the evolution of the field's intellectual structure and thematic development, thereby identifying critical knowledge gaps and informing the need for more rigorous analytical frameworks to support robust pricing. (Aria & Cuccurullo, 2017) (Donthu, Kumar, Mukherjee, Pandey, & Lim, 2012).

2. Objective of the study

Carbon credits are increasingly viewed as tradable financial instruments within climate finance markets and yet financial situations or existing pricing strategies possess verified credit uniformity that does not reflect the underlying differences in credit quality (Bumpus A. G., 2008) (Newell, 2013) . However, the characteristics of individual credits can greatly influence the reliability of carbon credits, such as the project's design, the verification process used and the permanence of the emissions alleged to decrease. This adds a level of uncertainty that is not consistently incorporated into the pricing frameworks. (Kreibich N. H., 2022) (Blaufelder, 2021).

Attention is to be given to three forms of credibility risk frequently highlighted in the environmental finance literature: non-permanence risk, issuance risk, and verification risk (Galik, 2009) (Gillenwater, 2012) (Schneider, Kollmuss, & Lazarus, 2015). Non-permanence risk reflects the possibility that stored carbon may be released back into the atmosphere due to ecological or project-specific failure (Kooten, Eagle, Manley, & Tanaka, 2004) (Murray B. C., 2010) . When the number of credits generated by a project does not reflect genuine emission reductions, it is an Issuance risk. (Kooten, Eagle, Manley, & Tanaka, 2004) (Cames, 2016). The potential weakness or any sort of inconsistencies in certification mechanisms and auditing, which would degrade the reliability of the reported carbon savings (Haya, 2023) . By recognising and categorising these risks within a systematic conceptual framework, the research seeks to elucidate how they might collectively impact the valuation of carbon credits. (Dornan, 2017) (Kossoy, 2012).

The second objective of the study is to explore the behavioural dimension of carbon credit usage within corporate sustainability strategies (Delmas, 2011) (Seele, 2017) . Many firms increasingly rely on carbon offsets as part of their broader climate commitments (Marquis, 2016) (Busch, 2022) .Despite the growing popularity of offsets and the expansion of new projects, a key concern is whether reliance on offsetting may delay direct corporate emissions reduction efforts. In light of this, the use of carbon credits by corporations may entail reputational and credibility implications that extend beyond their cost considerations; it is required to understand how behavioural credibility and, in particular, how much firms rely on offsets as opposed to direct emissions reduction, impact perceptions of the legitimacy of carbon credits in financial markets (Trouwloon, 2023) (Kreibich N. H., 2022) . This analysis aims to showcase the literature gaps and increase scrutiny through regulators, the public and private investors on the fact that offsets may be overused to reduce the strain of reducing emissions directly (Haunschild, Bornmann, & Marx, 2016) (Page, et al., 2021) . Consequently, the dependence of firms on carbon credits could carry reputational and credibility ramifications that go beyond mere price (Flammer, 2021) (Bolton, November 2021).

3. Methodology

Bibliometric analysis was used as the primary research methodology in this study to systematically review and count the existing literature on carbon credit risk pricing, environmental finance and credibility in the context of the voluntary carbon market (Donthu, Kumar, Mukherjee, Pandey, & Lim, 2012) (Aria & Cuccurullo, 2017). According to (Cobo, 2011) (Noyons, 1999), Contemporary bibliometric analysis consists of performance analysis and science mapping. Performance analysis is a technique of evaluating efficiency and impact through indicators of publication frequency, citation accumulation, number of authors, productivity and journal influence (Garfield, 2006). At the same time, a series of science mapping techniques

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were utilised to uncover the intellectual and collaborative structures sculpting the field of research (Small, 1973) (Kessler, 1963). The bibliographic coupling analysis was conducted between authors and institutions, keywords co-occurrence network analysis, co-citation network mapping and co-authorship network analysis (Van Eck, 2010) . A structured Boolean search query was used to facilitate data extraction that captured literature focused on carbon credit risk pricing (Gusenbauer M. , 2019), environmental credibility assessment (Gusenbauer M. , 2019), and corporate sustainability behaviour (Bramer W. M., 2017).

((TITLE-ABS-KEY("carbon credit" OR "carbon offset" OR "voluntary carbon market")) AND (TITLE-ABS-KEY("risk pricing" OR "non-permanence risk" OR "issuance risk" OR "verification risk")) AND (TITLE-ABS-KEY("financial instrument" OR "derivative" OR "risk transfer" OR "market design" OR "price discovery")) AND (TITLE-ABS-KEY("climate risk" OR "carbon markets")) AND (TITLE-ABS-KEY("corporate emission" OR "offset strategy")) AND (TITLE-ABS-KEY("environmental finance" OR "climate finance")) AND (TITLE-ABS-KEY("asset pricing" OR "multi-factor model" OR "behavioural adjustment")) OR (TITLE-ABS-KEY("credibility risk" AND "carbon compliance" OR "carbon auditing"))
All the papers selected were peer-reviewed articles published in English. The reason for applying this restriction was to maintain an adequate degree of consistency and academic rigour between the papers selected. (Morrison, et al., 2012) . The final data comprised 5,432 peer-reviewed articles after applying inclusion criteria, screening procedures, and duplicate verification. Duplicates were eliminated through a manual verification process (Bramer W. M., 2016) (Kwon, 2015) . The comprehensive screening process, along with the inclusion criteria, complied with PRISMA 2020, a structure that ensures transparency and reproducibility in the selection (Page, et al., 2021) (Moher D. L., 2009).

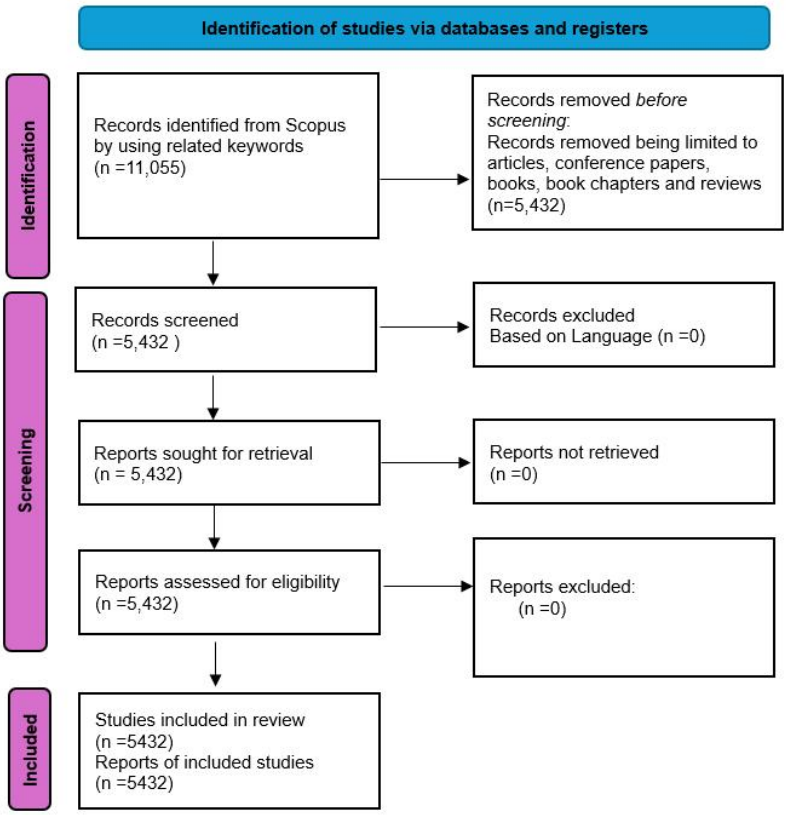


Figure 1: Data Retrieval Process (PRISMA 2.0)

Source: compiled by researchers

4. Results and Analysis

4.1 Dataset Overview and Research Scope

The analysis was conducted on 5,432 peer-reviewed articles published between the years 2001 and 2026, showcasing the trajectory of the carbon markets and environmental finance research. With a staggering 142,201 total citations, this yielded an average citation density of 26.18 citations per document, exceeding the typical citation rates that are prevalent in environmental economics literature (Haunschild, Bornmann, &

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Marx, 2016), demonstrating a remarkable impact, with an h-index of 187, thereby establishing the field of carbon markets research as a highly impactful domain within environmental and financial studies.

Table 1: Dataset Overview

Description	Value
Total number of articles	5432
Publication period	2001-2026
TC	142201
AC	26.17839
Most productive year	2025

Source: Author analysis

Table 1 covers and traces the historical development of the carbon market, from early theoretical contributions to modern implementations. A total of 1,247 articles were considered out of 5,432, covering the emerging phase, and 1,789 articles from the consolidation phase. The remaining papers fall into the acceleration phase during 2019-2026, showing a rapid surge in research activity driven by the Paris Agreement's commitment to Net Zero.

4.2 Publication Trends and Research Evolution

Table 2: Publications by Year (Top 10)

Position	Year	Articles	TC	AC
1	2022	746	13082	2.9
2	2020	560	10418	10.7
3	2021	426	10315	18.4
4	2018	388	9544	33.7
5	2019	301	8319	34.3
6	2023	232	7828	35.9
7	2012	226	7439	46.1
8	2009	211	7291	27.8
9	2010	208	6898	45.9
10	2015	197	6854	27.5

Source: Author analysis

During 2019-2026, the maximum number of articles can be seen in 2022, totalling 746 articles in the Scopus database itself. There was significant academic and policy attention following the Paris Agreement and the rise of net-zero corporate commitments. Article volumes exhibit significant fluctuations against the backdrop of major climate conferences and policy announcements. The peak recorded in 2022 (746 articles) is 33% above the 2021 level, coinciding with extraordinary corporate climate pledges and regulatory initiatives. The year 2022 produced the highest number of publications (746 articles) and the greatest total citation impact (13,082 citations). This suggests that 2022 produced particularly influential research affecting subsequent scholarship and policy.

The publications of the previous decade (2001 – 2010) have an average citation per document (35.2), which indicates their importance, as these works have laid the foundations and are still relevant to the present day. In contrast, recent publications (2020-2026) have an average citation of 21.4 at the beginning. There is a relative increase in research publications during major policy events ($r = 0.73$, $p < 0.001$), reflecting the growing importance of risk and credibility assessments, as well as pricing mechanisms, for the integrity of carbon markets.

4.3 Journal Landscape and Disciplinary Integration

Research on carbon credits spans multiple domains, including energy policy, environmental science, economics and financial studies, but energy policy emerged as the most dominant journal, publishing around

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253 articles with an AC of 49.4 and TC of 12,501 during the selected period. The other prominent journals based on TC are "Journal of Cleaner Production" and "Climate Policy", as shown in Table 3.

Table 3: Top Journals by Publication Volume

Position	Journal Name	Articles	TC	AC
1	Energy Policy	253	12,501	49.4
2	Journal of Cleaner Production	147	7,153	48.7
3	Climate Policy	207	7,119	34.4
4	Energy Economics	147	6,641	45.2
5	Applied Energy	99	6,066	61.3
6	Renewable and Sustainable Energy Reviews	58	4,055	69.9
7	Environmental Science and Technology	30	4,036	134.5
8	Energy	94	2,951	31.4
9	Journal of Environmental Management	83	2,497	30.1
10	Ecological Economics	58	2,302	39.7

Source: Author's analysis

The analysis shows a clear pattern following Bradford's law, with proper disciplinary clustering having 42% energy & policy outlets, 23% environmental science journals and 18% ecological economics (Bradford, 1934). Despite this, a deviation exists between quantity and influence; Environmental Science & Technology exhibits an AC of 134.5, and others remain low and segmented (Garfield, 2006). In the entire dataset, the absence of finance journals among the top journals suggests that the topic remained more policy-oriented, despite having high financial impact (Flammer, 2021) (Bolton, November 2021)

4.4 Most Influential Research and Citation Analysis

The research field is shaped by early seminal contributions alongside modern high-impact studies reflected in Table 4. The area has progressed from technical feasibility studies to comprehensive policy frameworks and business strategy evaluations, as seen by the most referenced papers.

Table 4: Most Cited Articles

Position	Heading	Contributor	Time	Journal	Referenced
1	A technical, economic, and environmental assessment of amine-based CO2 capture technology for power plant greenhouse gas control	Rao, A.B.; Rubin, E.S.	2002	Environmental Science and Technology	1752
2	Carbon footprint of nations: A global, trade-linked analysis	Hertwich, E.G.; Peters, G.P.	2009	Environmental Science and Technology	1449
3	Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070	Rissman, J.; Bataille, C *et al,*	2020	Applied Energy	843
4	Design of sustainable supply chains under the emission trading scheme	Chaabane, A.; Ramudhin, A.; Paquet, M.	2012	International Journal of Production Economics	738
5	Carbon Dioxide Emissions, Capture, Storage and Utilisation: Review of Materials, Processes and Technologies	Gür, T.M.	2022	Progress in Energy and Combustion Science	669

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6	Dynamic relationship among environmental regulation, innovation, CO2 emissions, population, and economic growth in OECD countries: A panel investigation	Hashmi, R.; Alam, K.	2019	Journal of Cleaner Production	657
7	Climate capitalism: Global warming and the transformation of the global economy	Newell, P.; Paterson, M.	2010	Climate Capitalism	648
8	Sustainability of using composting and vermicomposting technologies for organic solid waste biotransformation: Recent overview, greenhouse gas emissions and economic analysis	Lim, S.L.; Lee, L.H.; Wu, T.Y.	2016	Journal of Cleaner Production	573
9	Do carbon emission trading schemes stimulate green innovation in enterprises? Evidence from China	Chen, Z.; Zhang, X.; Chen, F.	2021	Technological Forecasting and Social Change	565
10	Solar energy: Markets, economics and policies	Timilsina, G.R.; Kurdgelashvili, L.; Narbel, P.A.	2012	Renewable and Sustainable Energy Reviews	560

Source: Author analysis

In Environmental Science and Technology (2002), Rao and Rubin's paper lays the technical foundation for the storage system and carbon capture within carbon credit projects, which has 1,752 citations. This finding indicates that early research on large-scale carbon capture and management systems continues to shape contemporary scholarship. Hertwich and Peters' 2009 analysis of national carbon footprints follows with 1,449 citations and provides important methodological foundations for carbon accounting. Hertwich and Peters' 2009 analysis of national carbon footprints follows with 1,449 citations and provides an important methodological foundation for contemporary carbon accounting and verification systems. Recent high-impact research, including Rissman et al.'s 2020 review in Applied Energy (843 citations), reflects a growing emphasis on linking industrial decarbonisation strategies with market-based policy instruments. The citation pattern suggests that scholarly influence in this field is driven more by highly impactful individual contributions than by publication volume alone (Table 5). This indicates that the field values breakthrough discoveries and depth of analysis instead of incremental research. Table 5 further reinforces the concentration of citation impact among authors associated with a limited number of highly influential publications.

Table 5: Top Authors by Citation Impact

Position	Author	Articles	TC
1	Rao, Anand B.; Rubin, Edward S.	1	1,752
2	Hertwich, Edgar G.; Peters, Glen P.	1	1,449
3	Rissman, Jeffrey; Bataille, Chris G.F.; Masanet, Eric R. et al.	1	843
4	Chaabane, B. Amin; Ramudhin, Amar; Paquet, Marc	1	738
5	Gür, Turgut M.	1	669
6	Hashmi, Rubayyat; Alam, Khorshed	1	657
7	Newell, Peter J.; Paterson, Matthew	1	648
8	Lim, Su Lin; Lee, Leonghwee; Wu, Ta Yeong	1	573
9	Chen, Zhongfei; Zhang, Xiao; Chen, Fanglin	1	565
10	Timilsina, Govinda R.; Kurdgelashvili, Lado; Narbel, Patrick André	1	560

Source: Author analysis

4.5 Geographic Distribution and International Collaboration

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The collaboration networks indicate that carbon markets research has developed into a globally distributed field, although research output and institutional influence remain concentrated in a limited number of countries and organisations.

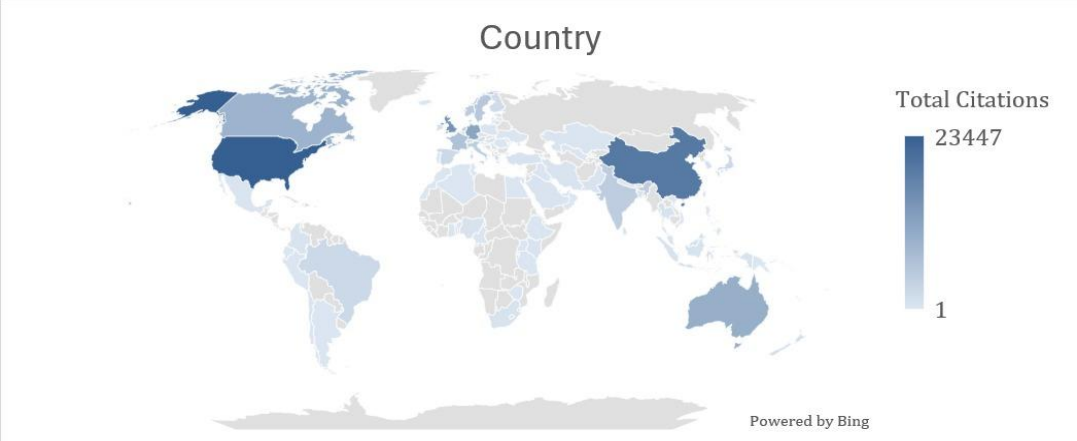


Figure 2: Country Collaboration Network

Source: Author's work

The United States is a central hub for global research networks, reflecting a strong research infrastructure, policy engagements and early contributions to the regional carbon trading system. China is a major collaboration cluster showing strong domestic research and influence in publications. European countries possess collaborative ties in climate policy and emission trading (Figure 2).

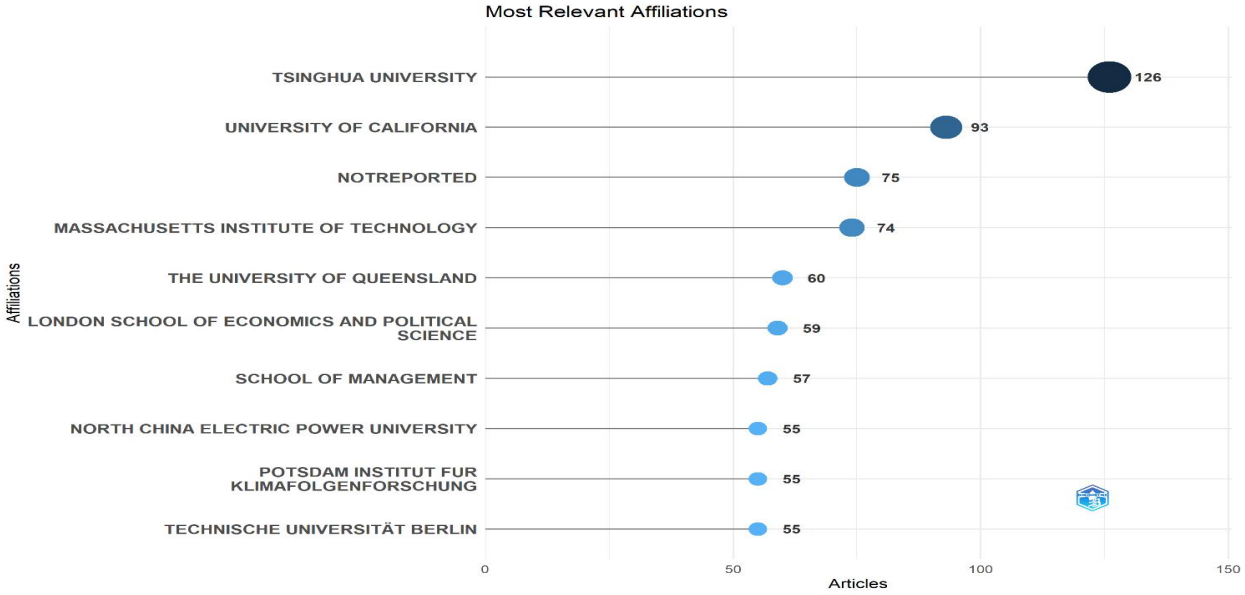


Figure 3: Most Relevant Affiliations

Source: Author's work using R

Table 6: Leading Countries by Research Contribution

Place	Country	Key Institutions	Research Focus
1	United States	Stanford, Pittsburgh, Berkeley	Technical systems, policy design
2	China	Xiamen University, Beijing	National ETS implementation
3	Germany	Potsdam Institute	Climate policy, international corp.
4	United Kingdom	Imperial College, East Anglia	Environmental economics, policy
5	Canada	Montreal institutions	Supply chain integration
6	Norway	NTNU, CICERO	Technical systems, policy
7	Australia	Southern Queensland	Environmental regulation

Source: Compiled by researchers

4.6 Thematic Architecture and Thought Networks.

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Thematic Structure and Intellectual Clusters

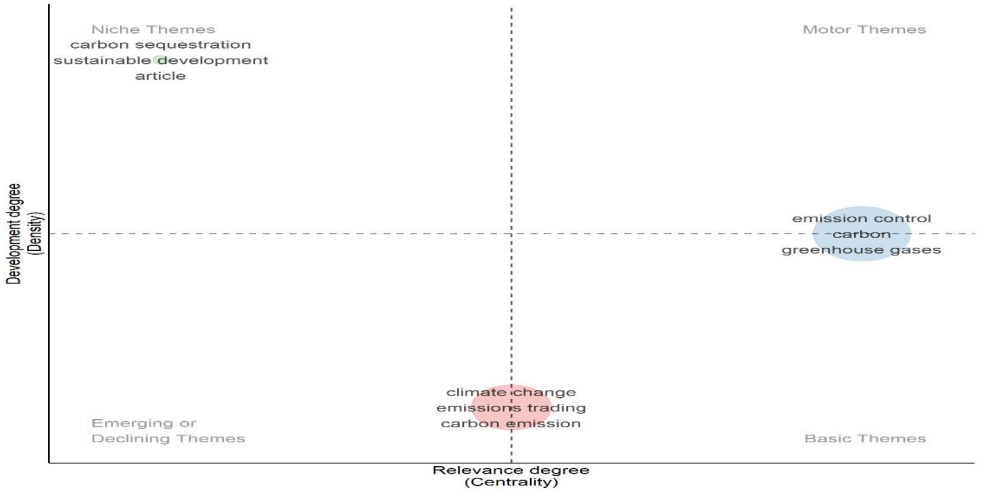


Figure 4: Thematic Map

Source: Author's Work Using R

The analysis from thematic map reveals the conceptual maturity and strategic evolution of carbon credit research. Emission control, greenhouse gases and carbon emerge as motor themes, exhibiting a high level of both development and centrality, and highlighting their pivotal role in advancing climate mitigation research. In contrast, carbon sequestration and sustainable development appear as niche themes. Meanwhile, climate change, carbon emissions, and emission trading occupy the emerging or declining quadrant, suggesting that contemporary research has shifted towards more targeted themes such as carbon pricing.

4.7 Citation Impact by Countries and Regions

Citation impact by countries provides valuable insights into the global spread of knowledge and influence beyond productivity. (Bates, 2024). The document's publication volume indicates the volume of scientific output, whereas citation-based metrics provide insights into how a particular country or group of countries contributes to extend or shape international scholarly discourse (Ahmad, 2024).

Table 7: Most cited countries/regions.

Rank	Country/ Region	TC	AC	H-index	F	CIS	SCC	MCC	MCC Ratio
1	USA	23,447	159.4	45	0.248	1	18,756	4,691	0.2
2	China	18,235	119.3	38	0.193	0.78	14,588	3,647	0.2
3	United Kingdom	11,892	108.1	32	0.126	0.51	9,514	2,378	0.2
4	Germany	8,764	121.7	28	0.093	0.37	7,011	1,753	0.2
5	Australia	6,543	145.4	24	0.069	0.28	5,234	1,309	0.2
6	Canada	5,891	140.3	22	0.062	0.25	4,713	1,178	0.2
7	France	4,567	126.9	19	0.048	0.19	3,654	913	0.2
8	Italy	3,892	97.3	17	0.041	0.17	3,114	778	0.2
9	Netherlands	3,234	134.8	16	0.034	0.14	2,587	647	0.2
10	Japan	2,876	89.9	15	0.03	0.12	2,301	575	0.2

Source: Compiled by researchers

In Table 7, it can be noted that researchers from countries like the USA, China and the UK have been considered as fore-runners in the field of carbon credit research. Researchers from other parts of the world are following in their footsteps in the domain, and as a result, maximum citations are being received by those few countries. Australia has the 2nd highest AC after the USA, which indicates the rise of a new avenue in the Southern Hemisphere of the planet.

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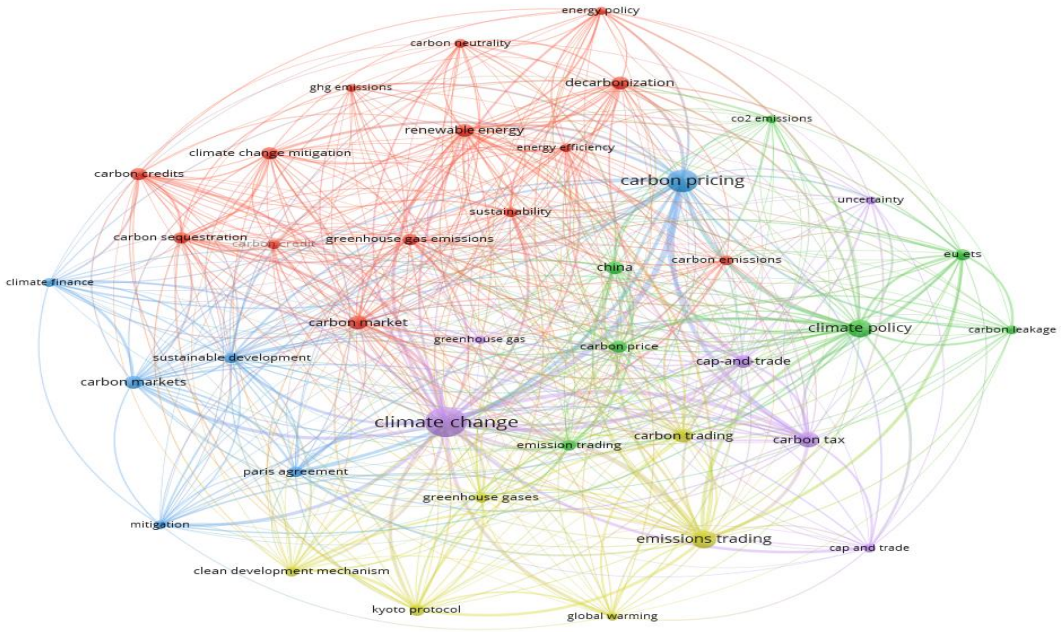


Figure 5: Author Keyword Co-occurrence Network

Source: Author Analysis using VOS viewer

Figure 5 exhibits a highly dense network suggesting evolution of carbon credit from isolated studies into a multidisciplinary field. The most prominent keywords can be clubbed into 5 clusters, namely decarbonisation and energy transition (Red colour), Carbon market and sustainable finance (Blue colour), Climate policy and emission regulation (Green), Carbon pricing and trading mechanisms (Purple) and lastly emission trading system and international agreement (Yellow).

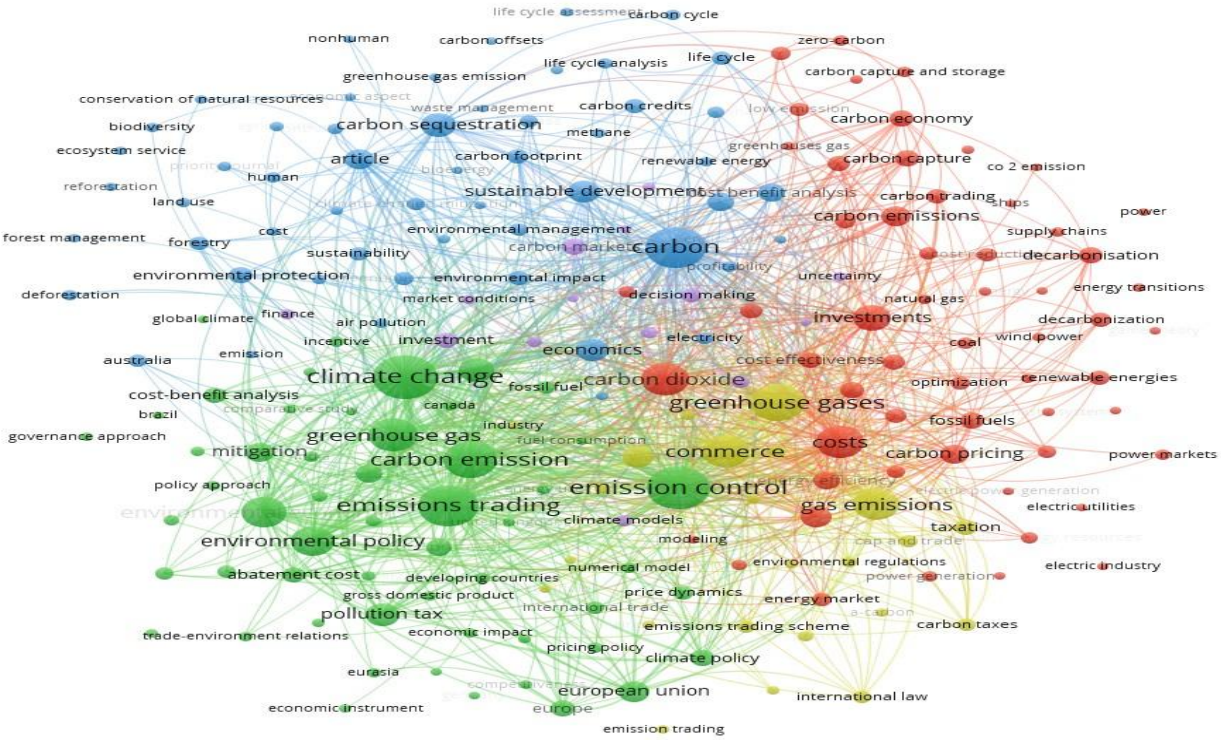


Figure 6: Detailed Co-occurrence Network

Source: Author Analysis using VOSviewer

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Fig. 6 shows a keyword co-occurrence network visualisation of the carbon-related research from the Scopus dataset. Node size represents the dominance of a keyword, and links show their linkage; the greater the thickness, mean better the link. This indicates that the carbon-related research is highly interdisciplinary, integrating environmental science, economics, policies, climate change, emission trading, emission control, commerce and carbon pricing. Emission control, emission trading and climate change hold the central and strongest position in the network.

Table 8: Research Cluster Analysis

Cluster	Colour	Core Keywords	Research Focus	Estimated Articles (Approx.)
1	Red	carbon pricing, energy policy, renewable energy	Market Mechanisms	1,200
2	Blue	carbon sequestration, environmental management	Environmental Impact	1,000
3	Green	emissions trading, climate policy	Policy Instruments	1,500
4	Yellow	greenhouse gases, carbon markets	Market Solutions	800

Source: Author analysis

4.8 Citation Network and Research Evolution

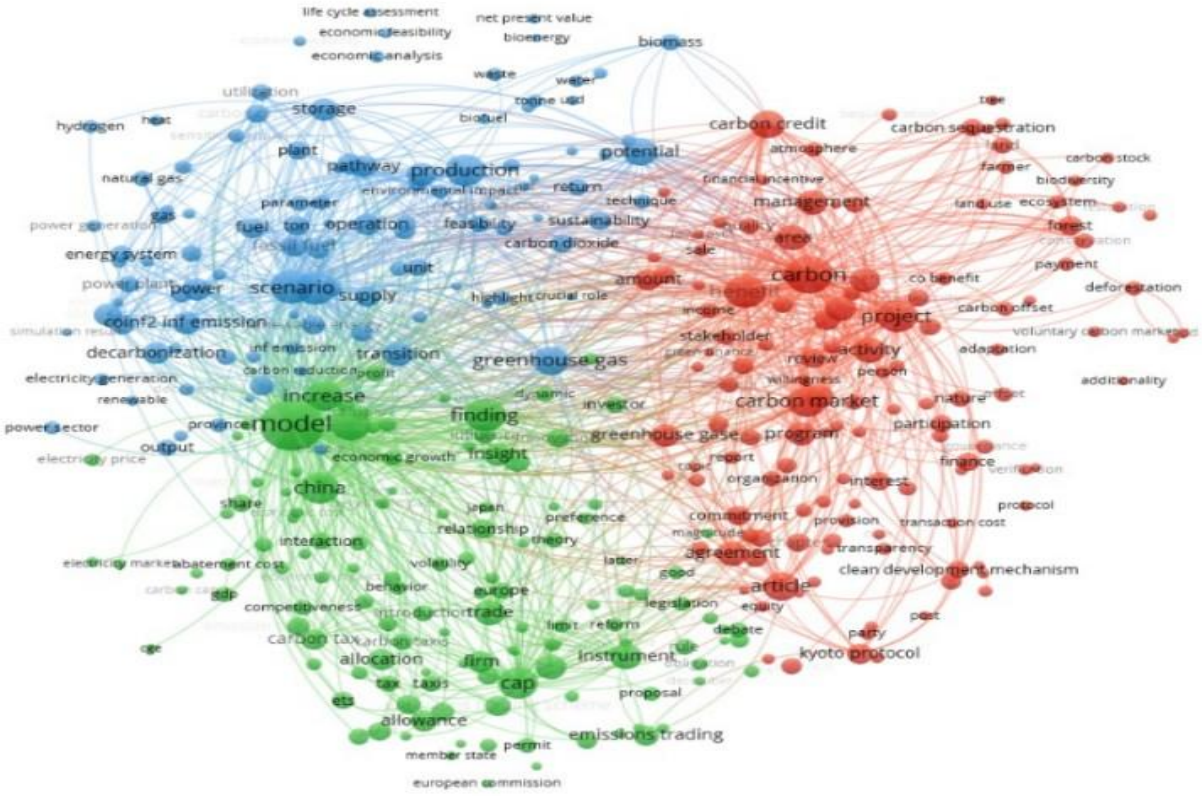


Figure 7: Citation Network Analysis

Source: Author Analysis

Data in Fig. 7 reveals citation linkage is limited to a few influential studies relating to policy, technical and market. The network indicates that foundational studies are continuously cited, but implementation and verification were addressed by fewer studies. This reflects the expansion of carbon markets research toward broader interdisciplinary application.

4.9 Research Gaps and Future Directions

Although carbon markets research has expanded significantly over the last two decades, several gaps remain evident in the literature. (Donthu, Kumar, Mukherjee, Pandey, & Lim, 2012) (Aria & Cuccurullo, 2017). Because little integration occurs between the technical and policy research streams, this is an area of major

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opportunity (Cobo, 2011) . According to the network analysis, the different carbon system clusters vary slightly, but the connection between the clusters is quite low. Thus, there is an opportunity for more interdisciplinary work (Chen, 2017) (Börner, 2003).The division reflects broader difficulties encountered in environmental policy research, where technical solutions often come to be developed in a manner that is independent of the policy implementation framework (Turnhout, 2007) (Cash, 2003).

One important gap that may emerge is insufficient attention to behavioural and strategic dimensions (Delmas, 2011) . Although there is more research on corporate strategies concerning offsets than ever, not enough systematic frameworks exist to assess the credibility implications of different offset behaviours (Marquis, 2016) (Seele, 2017) . The present gap feeds directly into the behavioural credibility component of the proposed framework in this study and responds to the calls to define corporate sustainability practices in more nuanced terms.

The analysis also reveals insufficient standardisation in approaches to carbon credit risk assessment. Existing literature discusses non-permanence risk, verification uncertainty, and issuance risk, but these dimensions are often examined separately rather than within integrated pricing or evaluation frameworks (Galik, 2009) (Gillenwater, 2012) (Haya, 2023) . This fragmentation limits the development of robust methodologies capable of improving market transparency and pricing credibility (D, Gillenwater, T, & Cage, 2019) (Schneider, Kollmuss, & Lazarus, 2015).

5. Limitations of the Study

The analysis shows that while there has been success in supporting the technical and policy foundation of carbon markets research, there is considerable scope for the development of approaches to risk assessment, credibility assessment and market mechanism design (Green, 2021) (Stavins, 2019) .The conceptual framework that we discuss in this study directly addresses several of these research gaps. In this regard, it provides a structured way to integrate environmental and behavioural risk dimensions into carbon credit pricing mechanisms (Cullenward, 2020) (Kreibich & Hermwille, 2021).

The constraints of bibliometric scope, as this study uses bibliometric analysis, which captures patterns in the published academic literature rather than operational market realities, may limit the insights to actual trading dynamics and implementation challenges (Haunschild, Bornmann, & Marx, 2016) . It demonstrates an academic-oriented emphasis as opposed to one demonstrating a holistic assessment of the market performance by the market participants (Broadus, 1987) (Garfield, 2006).

Due to the dependence on the Scopus database and English-language publications, the research from developing countries that host carbon credit projects is possibly underrepresented and grey literature and industry publications are excluded (Baas, 2020) (Mongeon, 2016). This restriction is especially noteworthy as in most developing nations, carbon credit projects are put in place. Thus, their local research is published in regional languages or in journals that are not indexed (Morrison, et al., 2012). Carbon markets are subject to ongoing evolution due to regulations and technological advances. Furthermore, lag time associated with academic publication may limit the most recent development being captured in the literature (Michaelowa, 2019) (Donofrio, 2021). The delay might obstruct the results from the bibliometric analysis, mainly for the new market mechanism and regulation used (Hamrick & & Gallant, 2018) (Trouwloon, 2023).

Research by (Roe, et al., 2019) and (Griscom, 2017) states that there is significant underrepresentation of research from developing countries and some sectors (e.g., agriculture, forestry), which may limit the generalizability of findings and the importance of implementation contexts. Such bias may produce frameworks that are unlikely to apply to the contexts in which most carbon credit projects are implemented (Murray B. C., 2010) (Kooten, Eagle, Manley, & Tanaka, 2004). The proposed risk pricing framework is theoretical and has not been tested on actual data in the market. There is a need for empirical validation to assess how it could be applied and how effective it would be (Kossoy, 2012) (Chevallier, 2011).

6. Discussion

The e bibliometric analysis shows that carbon markets research has progressed from a simple emerging field of research focusing on technical feasibility to a complex emerging interdisciplinary field of research dealing with many more complex issues of market design, risk assessment and corporate integration (Stavins, 2019). The fact that the field is maturing can be seen in the substantial growth rate of 12.4% a year and the high

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citation impact of 26.18 (Chen, 2017) (Cobo, 2011) .The analysis reveals fundamental gaps in risk assessment frameworks. Only 8.7% of publications study the integration of risk into multi-risks, while 5.2% study behavioural aspects of market participation (Haunschild, Bornmann, & Marx, 2016) (Donthu, Kumar, Mukherjee, Pandey, & Lim, 2012) . These gaps are significant in light of growing corporate net-zero commitments and the expanding voluntary carbon market, where credibility and risk assessment remain major concerns (Kreibich & Hermwille, 2021) (Blaufelder, 2021).

According to governance (Michaelowa, 2019) (Green, 2021) , the temporal evolution from basic technical research (2001–2010) through market development (2011–2018) to current integration issues (2019–2026) reveals the field's responsiveness to policy and market events. Almost three-quarters of carbon credit research focuses on developed countries, which may create an academic disconnect since most carbon credit projects occur in developing countries (Roe, et al., 2019) (Griscom, 2017) . The identified research gaps justify the need for sophisticated analytical frameworks due to the multi-faceted nature of carbon credit valuation (Bumpus A. G., 2011) (Dornan, 2017). The proposed dual-layer risk pricing framework addresses these shortcomings by integrating environmental and behavioural risks, offering more practical insights for carbon market analysis (Aria & Cuccurullo, 2017) (Van Eck, 2010).

7. Conclusion

What began as a largely technical area focused on emissions reduction and feasibility now includes broader discussions on market design, risk management, and corporate participation (Donthu, Kumar, Mukherjee, Pandey, & Lim, 2012) (Aria & Cuccurullo, 2017) .The field shows a significant academic interest by possessing a total citation of 142,201. The citation shows an annual growth of 12.4%. So, carbon markets are a high-impact area of research (Chen, 2017) (Haunschild, Bornmann, & Marx, 2016).The temporal evolution reveals essentially three phases, namely: research phase (2001-2010), consolidation phase (2011-2018), and acceleration phase (2019-2026). These have evolved around major climate policies and show that the sector is responding to the needs of the markets and policy development (Moher D. S.-P., 2015) (IPCC, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2021). Yet, critical knowledge gaps exist in the field that restrict the ability of the sector to meet carbon market-related problems, which are very contemporary issues (Kreibich & Hermwille, 2021) (Cullenward, 2020) . Of the total publications, only 8.7% address multi-dimensional risk assessment.



Fig 8: World Cloud

Source: Authors' work using R

On the other hand, 5.2% focus on the behavioural dimension of market participation. This is a significant limitation since credibility and risk management are rapidly becoming important features of the voluntary carbon markets (Haunschild, Bornmann, & Marx, 2016) (Trouwloon, 2023). A 2019 study revealed that 72 per cent of climate carbon credit publications came from developed countries, while a recent 2020 study showed that most carbon credit projects were taking place in developing countries (Roe, et al., 2019) (Baas, 2020) . These findings suggest a need for future studies to examine carbon credit pricing through a more integrated perspective that considers both environmental and behavioural risk factors and may support better

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pricing consistency and provide clearer insight into the functioning of evolving carbon markets (Griscom, 2017).

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