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Carbon Credits: Basics, the Role of ICTs, and a bibliometric literature review

Juan David Rivera-Niquepa [1,2], William Zuluaga [2], and Alix E. Rojas [2,✉]

[1]*Los Andes University, Bogotá D.C., Colombia*
jd.rivera@uniandes.edu.co
[2]*Universidad Ean, Bogotá D.C., Colombia*
{jrivera95412, wzuluaga, aerojash}@universidadean.edu.co

Abstract

Carbon credits have emerged as a crucial tool in mitigating greenhouse gas (GHG) emissions and addressing climate change challenges. This paper delves into the fundamentals of carbon credits, examining their benefits, including their pragmatic role in achieving global climate goals and reducing emissions amidst a rapidly changing climate. Moreover, the paper explores how emerging technologies are being leveraged to address challenges associated with carbon credit implementation, offering innovative solutions to enhance their effectiveness. Through an exploration of market-based solutions aligned with sustainable development principles and technological innovations, the paper comprehensively reviews recent literature on carbon credits. It offers insights into the evolving landscape of carbon credit projects, their environmental integrity, and the associated risks and implications for their implementation. By synthesizing existing knowledge and identifying gaps in the literature, this paper contributes to a deeper understanding of carbon credits and their potential role in achieving climate change mitigation goals. Furthermore, it provides a valuable resource for policymakers, researchers, and practitioners involved in carbon credit projects. It offers guidance on best practices and strategies for maximizing their impact in combating climate change.

Keywords: Carbon Credits · Climate change · Sustainable Development · Green Finance

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1 Introduction

Climate change is a pressing global challenge resulting from the accumulation of greenhouse gases (GHGs) in the Earth's atmosphere. It is primarily caused by human activities, such as burning fossil fuels, deforestation, and industrial processes, which release large amounts of carbon dioxide (CO2) and other GHGs into the atmosphere. Climate change poses significant risks to ecosystems, human well-being, and economic stability [1]. Various strategies and mechanisms have been developed to mitigate climate change, including carbon credits (CCs). They are tradable permits representing reducing or removing one metric ton of CO2 or its equivalent GHGs from the atmosphere. They incentivize and finance projects that reduce emissions or contribute to carbon sequestration; they're key components of carbon markets and provide economic incentives for emission reductions and the transition to a low-carbon economy [2].

CCs could be a profitable mechanism for addressing climate change by encouraging aging companies, countries, and individuals to take responsibility for their emissions. They can be used to offset or

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compensate for carbon footprints, which refer to the total amount of GHG emissions produced by an entity. By purchasing carbon credits, individuals and organizations can offset emissions by supporting emission reduction projects elsewhere, such as renewable energy initiatives, reforestation efforts, or energy efficiency improvements [3].

Despite the growing recognition of the importance of carbon credits in addressing climate change, there remains a need for a comprehensive conceptualization of the subject. This paper aims to fill this gap by thoroughly examining the benefits and challenges associated with carbon credits. By synthesizing existing literature and offering insights into the intricacies of carbon credit mechanisms, we contribute to the existing literature by offering a holistic understanding of this critical tool for mitigating climate change. Through our analysis, we shed light on the complexities of carbon credit markets, the environmental integrity of carbon offset projects, and the role of Information and Communication Technologies (ICTs) in enhancing carbon credit systems. This paper is a valuable resource for policymakers, researchers, and practitioners seeking to navigate the evolving landscape of carbon markets and foster sustainable solutions to climate change.

The remainder of this paper is organized as follows: Section 2 provides the theoretical framework, detailing the background and basics of carbon credits. Section 3 describes the proposed methodology for the literature review. Section 4 presents the study's results, which include subsections on Scopus Database Results, Web of Science Database Results, Google Trends Analysis, Environmental Integrity, Benefits and Challenges, and ICTs Perspectives. Section 5 contains the conclusions, where the study's findings are summarized and implications for future research are discussed.

2 Theorical Framework

The notion of carbon credits arose as a reaction to the growing acknowledgment of climate change as a worldwide threat. In 1966, economist Thomas Crocker put up one of the first ideas for carbon trading, which involved using market processes to tackle pollution issues, namely carbon dioxide emissions. Nevertheless, the establishment of carbon trading in its current form can be attributed to the Kyoto Protocol of 1997. The Kyoto Protocol implemented the Clean Development Mechanism (CDM) and carbon trading as strategies to decrease global greenhouse gas emissions.

After implementing the Kyoto Protocol, carbon credits became popular as governments sought to reduce emissions. European Union countries adopted carbon trading through the European Union Emissions Trading System (EU ETS), which started functioning in 2005. The EU ETS is a prominent carbon market on a global scale and has had a substantial impact on the establishment of carbon trading systems in other parts of the world.

Carbon credits are transferable rights that symbolize the entitlement to release a specific quantity of greenhouse gases, usually expressed in metric tons of carbon dioxide equivalent (CO2e). The fundamental concept is to establish a financial motivation for decreasing emissions by attributing a monetary worth to every metric ton of emissions that is prevented, diminished, or stored.

Carbon credits function under a cap-and-trade framework, in which a governing body limits overall emissions and distributes or sells emission allowances to regulated businesses, such as power stations or industrial sites. Entities that emit less than their allocated permits can sell surplus credits to those who exceed their allowances, thus establishing a market for exchanging carbon credits.

CCs are tradable permits or certificates representing the reduction or removal of one metric ton of CO2 or its equivalent greenhouse gases (GHGs) from the atmosphere[4]. They are a key component of carbon markets, incentivizing and financing projects that reduce emissions or contribute to carbon sequestration. The concept is based on the principle that GHG emissions are a global problem, and it doesn't matter where emissions are reduced as long as the overall emissions are reduced. By purchasing CCs produced by initiatives that lower emissions or remove carbon from the atmosphere, nations, organizations, or individuals can offset their emissions.

They can be generated by various projects, such as renewable energy projects, reforestation and afforestation initiatives, methane capture from landfills, energy efficiency improvements, and others contributing to reducing GHG emissions. Tiny projects could potentially reduce greenhouse gas (GHG) emissions and thus qualify for generating carbon credits, depending on their impact on emissions reduction and compliance with established standards and methodologies, simply by promoting solar energy for water desalination or purification, displacing the need for fossil fuel-based energy sources [5]. Inclusively, smart city projects may involve implementing various sustainable urban development initiatives to reduce energy consumption, improve waste management, promote green transportation, or enhance overall resource efficiency within a city [6]. However, it's important to note that the eligibility of projects for generating carbon credits depends on various factors, including the methodologies used for quantifying emission reductions, the credibility of monitoring and verification processes, and compliance with applicable standards and regulations. Each project must undergo a rigorous evaluation to determine its eligibility for carbon credit generation [7].

Once CCs are generated, they can be bought and sold on carbon markets. Buyers, such as companies or individuals seeking to offset their emissions, purchase these credits to compensate for them. The revenue generated from the sale of credits provides financial support to the projects that generated them, thus encouraging further emission reduction activities[2]. Thus, they play a significant role in climate change mitigation efforts by providing economic incentives for emission reductions and promoting the transition to a low-carbon economy. They are commonly used as a tool for companies and countries to meet their emission reduction targets, comply with regulations, or demonstrate environmental responsibility.

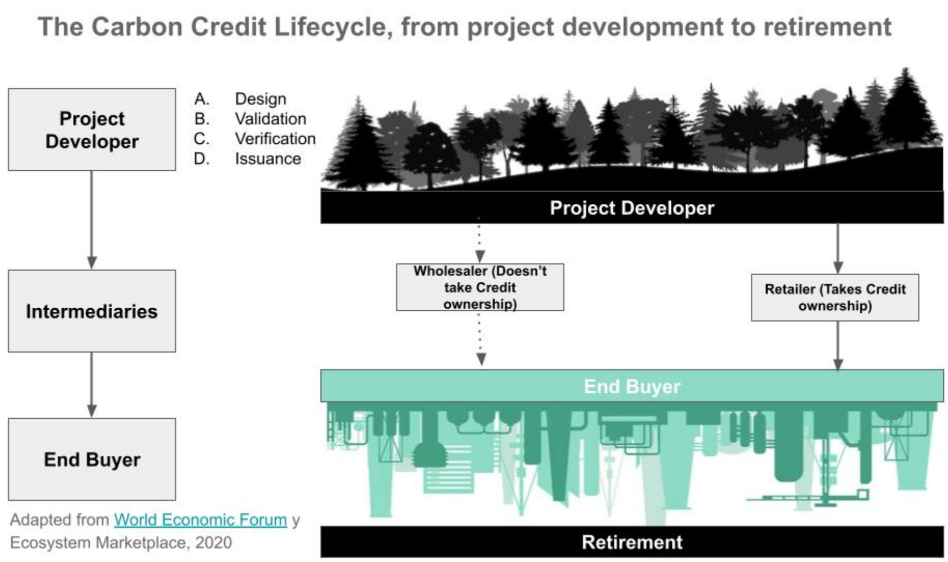


Figure 1: The Carbon Credit Lifecycle, from project development to retirement.

Following Figure 1, the logic behind a Carbon Credit is simple. A company that cannot stop emitting CO2 but wants or needs to do so. For this, It must purchase CCs in the carbon market (i.e., a CC End buyer), so it can ask another party (a Project Developer) to emit less CO2. In this case, even if a company still emits CO2, the total carbon in the atmosphere is reduced. CCs are generally traded in units of 1 tonne of (CO_2)[8]. To provide carbon credits (CCs), the Project Developer undergoes several essential steps:

A) Identification and Design of Projects: The Project Developer identifies and designs projects to reduce carbon emissions, ensuring they meet specific criteria and follow established methodologies and protocols.

B) Validation of Emissions Baseline: Once the project is designed, the Project Developer establishes a baseline for emissions, verifying the expected emissions reduction potential of the project.

C) Third-Party Verification: A third party then independently verifies the emissions baseline to confirm the project's impact on emissions reduction.

D) Registration and Issuance: Upon successful verification, the Project Developer registers the project in an approved registry and issues the corresponding carbon credits, providing evidence of the reduced emissions.

Speculative investors, including brokers, traders, and exchanges, participate in the carbon market by purchasing carbon credits as intermediaries. End buyers can procure carbon credits directly from project developers, wholesalers, or retailers. Regardless of the source, all carbon credits must be retired once utilized to offset emissions, ensuring transparency and preventing double accounting.

The life cycle of a carbon credit typically encompasses various stages, including project development, validation, registration, implementation, monitoring, and verification [6]. Projects eligible for carbon credits must demonstrate additionality, reducing emissions beyond what would have occurred without the project [7]. Once verified, carbon credits can be traded on carbon markets or retired to offset emissions. For instance, a renewable energy project may generate carbon credits by displacing fossil fuel-based electricity generation, thereby reducing greenhouse gas emissions. The project undergoes validation and verification to demonstrate environmental integrity and additionality. Once certified, the carbon credits can be sold to entities seeking to offset their emissions, providing a financial incentive for renewable energy development.

While carbon credits offer a mechanism for incentivizing emission reductions, they are not without their challenges. One criticism is the potential for greenwashing, where entities purchase carbon credits for reputation management without implementing meaningful emission reduction measures [8]. Additionally, concerns have been raised about the effectiveness of carbon offset projects in achieving long-term emission reductions and addressing social and environmental co-benefits [9].

Ultimately, understanding the theoretical foundations of carbon credits is crucial for grasping their functioning, adoption, and usefulness to encourage emission reductions and transition to a low-carbon economy. Having established this basis, it will explore the approach for conducting a bibliometric analysis of the literature on carbon credits, as described in the subsequent section.

3 Methodology

The purpose of conducting a bibliometric review in the context of carbon credits research is multifaceted, providing a comprehensive understanding of the existing literature landscape, identifying emerging trends and patterns, and pinpointing knowledge gaps within the field. Through a systematic analysis of scholarly publications, the bibliometric review aims to map the breadth and depth of research related to carbon credits, offering insights that inform future research directions and evidence-based decision-making.

One primary objective of the bibliometric review is to map the literature on carbon credits, identifying key authors, journals, and research topics. By analyzing publication trends over time, researchers can discern patterns in research focus, methodologies employed, and geographic distribution of scholarly contributions. Additionally, the review seeks to identify influential works and research clusters within the field, providing a holistic view of the current knowledge surrounding carbon credits.

Furthermore, the bibliometric review highlights emerging trends and knowledge gaps in carbon credit research. By systematically analyzing publication trends and citation patterns, researchers can identify areas where research is burgeoning and where further investigation is needed. This includes

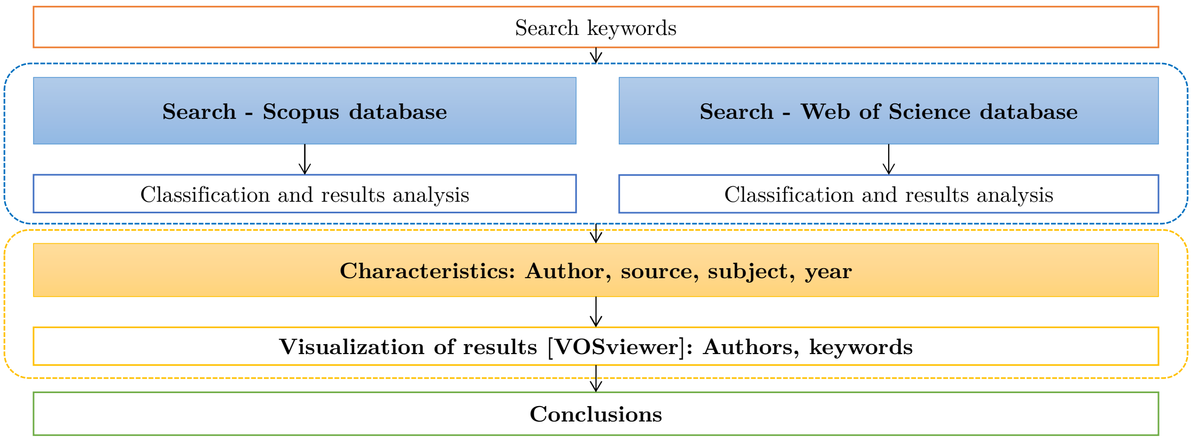


Figure 2: Methodological framework.

exploring topics such as the environmental integrity of carbon offset projects, the benefits and challenges associated with carbon credit implementation, and the role of Information and Communication Technologies (ICTs) in shaping carbon credit systems. The review addresses research questions such as: What predominant methodologies are employed in assessing the environmental integrity of carbon offset projects? What are the primary benefits and challenges in the literature regarding carbon credit implementation? How have ICTs influenced the design and operation of carbon credit systems, and what are the implications for climate change mitigation strategies?

By systematically addressing these research questions and synthesizing findings from the bibliometric review, researchers can provide valuable insights into the current state of carbon credit research, inform evidence-based decision-making, and guide future research efforts to address pressing challenges in climate change mitigation.

The proposed methodology for the literature review is structured in four sequential stages, as illustrated in Figure 2. It shows the four main stages of analysis. First, the keywords that determine the bibliometric search are defined. Subsequently, the defined keywords are used for the database review. The ScienceDirect and Web of Science databases are used as references. The results are obtained and analyzed independently. Then, the results are classified, taking into account the authors, sources, subjects, and year of publication. Then, the VOSviewer tool is used to classify and visualize the results.

4 Results

The results obtained from the methodology developed are presented below. As a result of the first stage, the keyword *carbon credits* was used, and each database was searched. In the Scopus database, 736 articles related to the keyword were identified. In the case of the Web of Science database, 4382 related documents were identified. The analysis for each group of information is summarized below.

4.1 Scopus Database Results

The Vosviewer software was used to visualize the level of keyword matches in the information set. This tool uses classification techniques to define clusters that relate to groups of keywords. Figure 3 shows the classification results of the 736 documents obtained from the Scopus database.

Figure 3 shows seven clusters identified in the entire data set. However, three dominant clusters

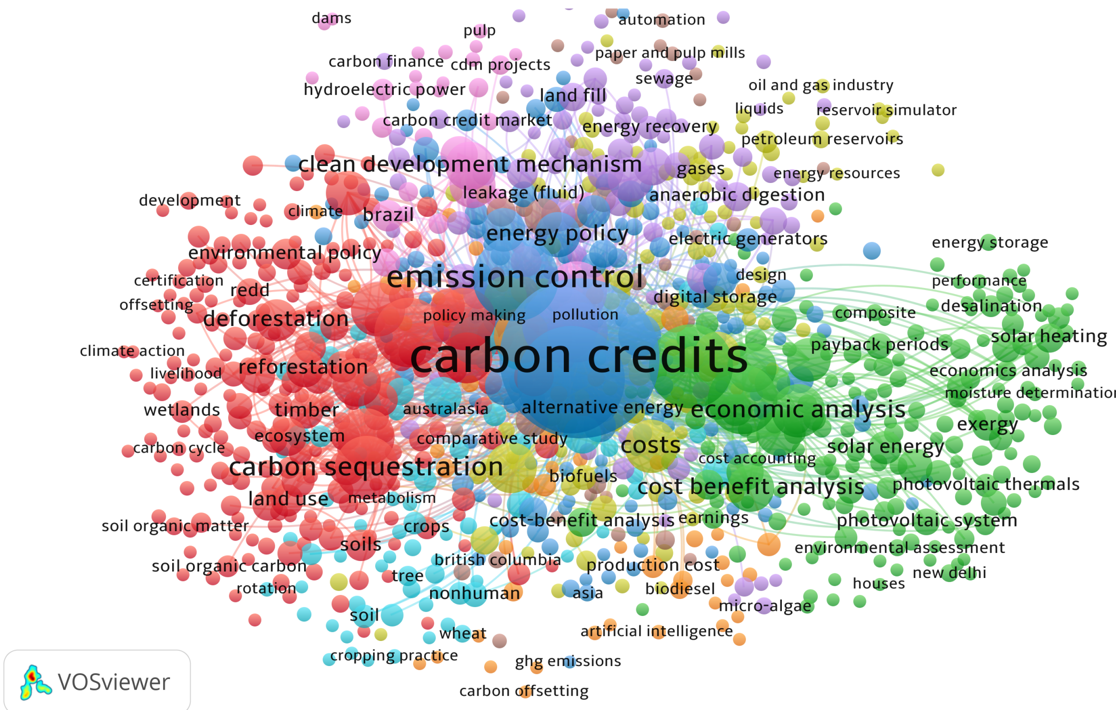


Figure 3: Classification Results - Keywords - Scopus.

stand out. The first (blue) contains keywords such as carbon credits, emissions control, policy making and energy policy. The second (red color) has a mostly environmental focus. It contains keywords such as deforestation, reforestation, carbon sequestration, ecosystems, land use and environmental policy. On the other hand, the green cluster contains keywords such as: economic analysis, cost-benefit analysis, solar energy, solar heating and payback period. This classification analysis allows observing the cross-cutting nature of the subject of carbon credits. The lines of research are mainly focused on political, economic, environmental and energy aspects.

Figure 4 shows the results of the classification analysis based on authors. The same sample of 736 documents was used with the restriction of authors with the highest number of coincidences in published articles.It clearly shows that the authors Tiwari, G.N and Kumar A have a significant share of contributions in the field of carbon credits in the Scopus database. Figure 4 presents the main statistics obtained for the ranking in authors, journals, topics and number of publications per year. These results show an overview of recent research on carbon credits in the Scopus database.

4.2 Web of Science Database Results

A similar procedure was followed for the Web of Science database. The keyword *carbon credits* was used and 4382 related documents were obtained. Subsequently, Vosviewer software was used to classify the database into keyword matches and chronological publication. The results of the clusters are shown in Figure 5.

Figure 5 (a) shows the clusters identified in the dataset. In this case, despite using more references than Scopus, the results clearly show the conformation of five clusters. The cluster marked in red brings together technological aspects, including keywords such as electricity, transportation, carbon markets, and blockchain. The cluster in green shows an environmental policy focus with keywords such as policy, green credits, environmental regulation, and impact. The cluster in yellow addresses sustainability with words such as sustainable development, clean development mechanisms, and emission reduction certificates. The blue cluster includes keywords such as climate change, cost,

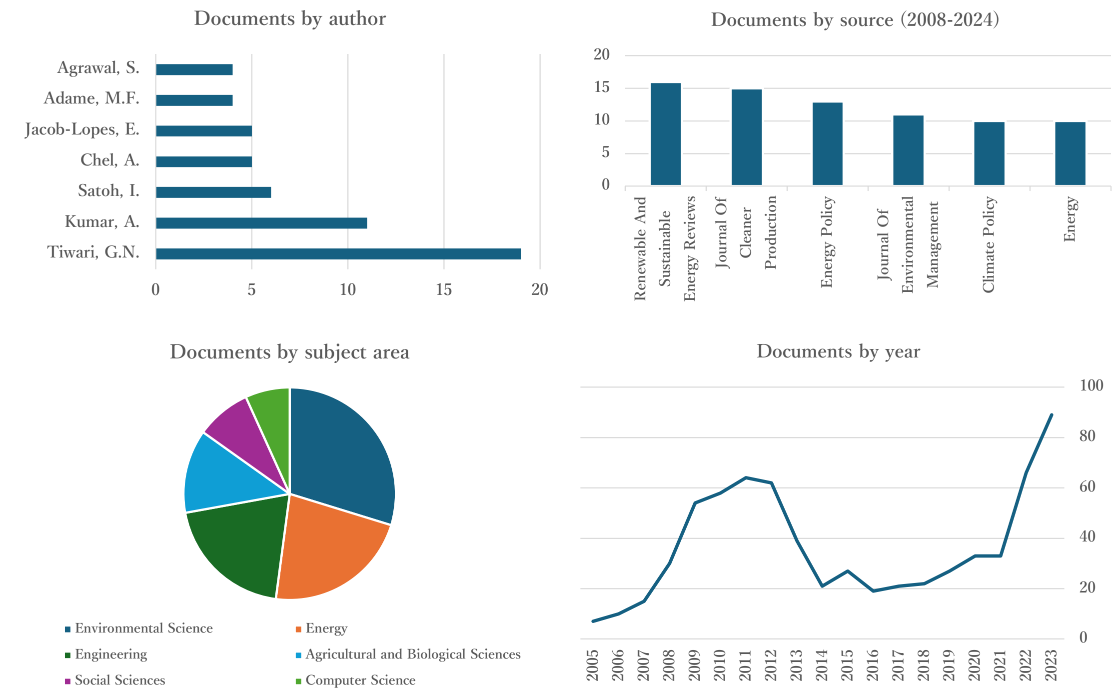
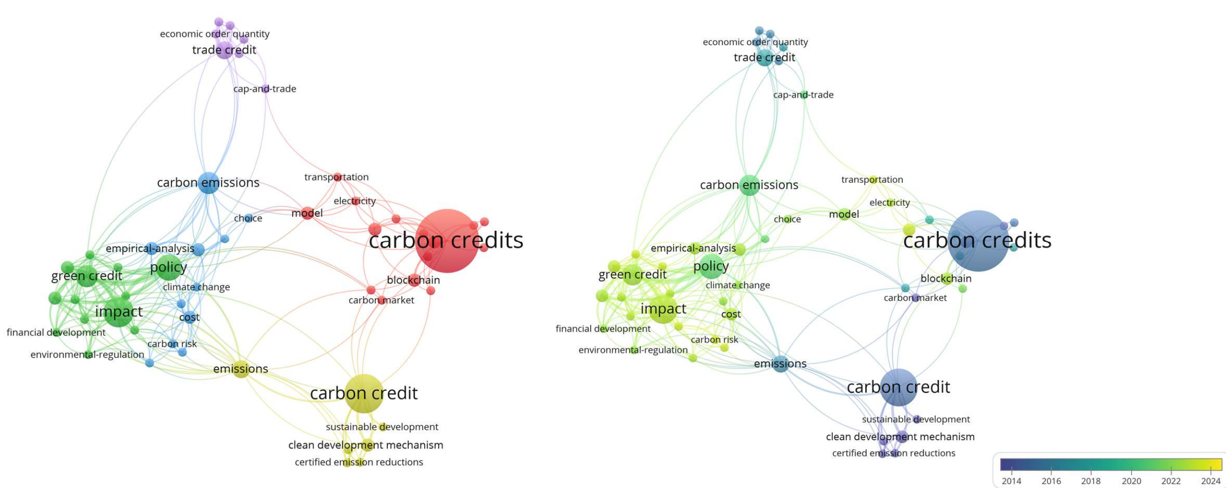


Figure 4: Statistics - Scopus.



(a) (b)

Figure 5: Classification Results - Keywords - Web of Science.

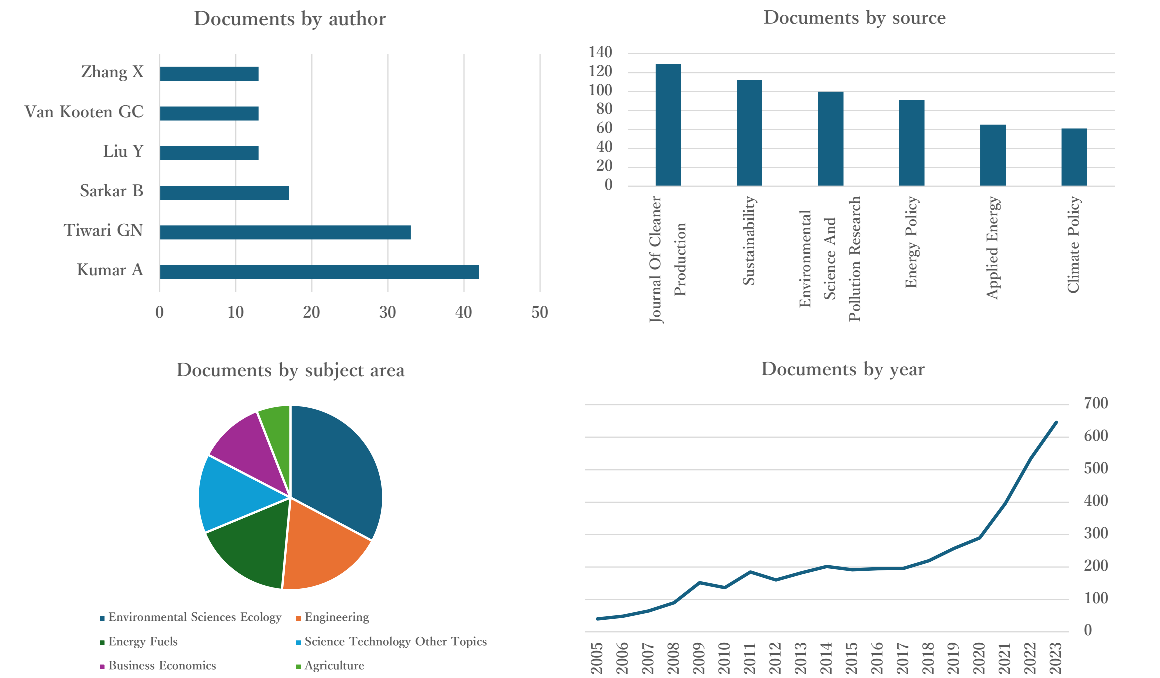


Figure 6: Statistics - Web of Science.

and carbon emissions. Finally, the purple cluster includes other market factors such as trade credit, economic order quantity, and cap-and-trade.

Figure 6 summarizes the main statistics of the Web of Science database. The aspects of authors, journals, subject areas and publications by year were again used. Some common coincidences between the two databases are observed. Again, Kumar. A and Tiwari. G.N as the most prolific authors in the field. As for the journals that publish the most in the field, the Journal Of Cleaner Production, Energy Policy and Climate Policy coincide. The dominant thematic areas are Environmental Sciences, Engineering and Energy. Finally, concerning the frequency of publications, a significant increase is observed in the two databases from 2021 onwards.

4.3 Google Trends Analysis

An analysis from Google Trends has been incorporated into the bibliometric review, clarifying that Google Trends data is not a traditional bibliometric data source like academic databases. It is included with the sole objective of offering complementary insights by providing information on public interest and awareness of carbon credits [9]. For example, identify spikes in this topic and related topics over time.

Google Trends analysis revealed intriguing patterns in the public interest and awareness surrounding carbon credits and their relationship with information and communication technologies (ICTs). As Fig. 7 shows, over the past decade, search interest in 'carbon credits' has steadily increased, reflecting a growing global awareness of the importance of carbon offsets in mitigating climate change. Interestingly, regional variations in search interest were observed, with higher levels of interest observed in regions actively participating in carbon markets, such as New Zealand. Moreover, a notable spike in search interest coincided with significant policy announcements and climate-related events, highlighting the responsiveness of public interest to external stimuli.

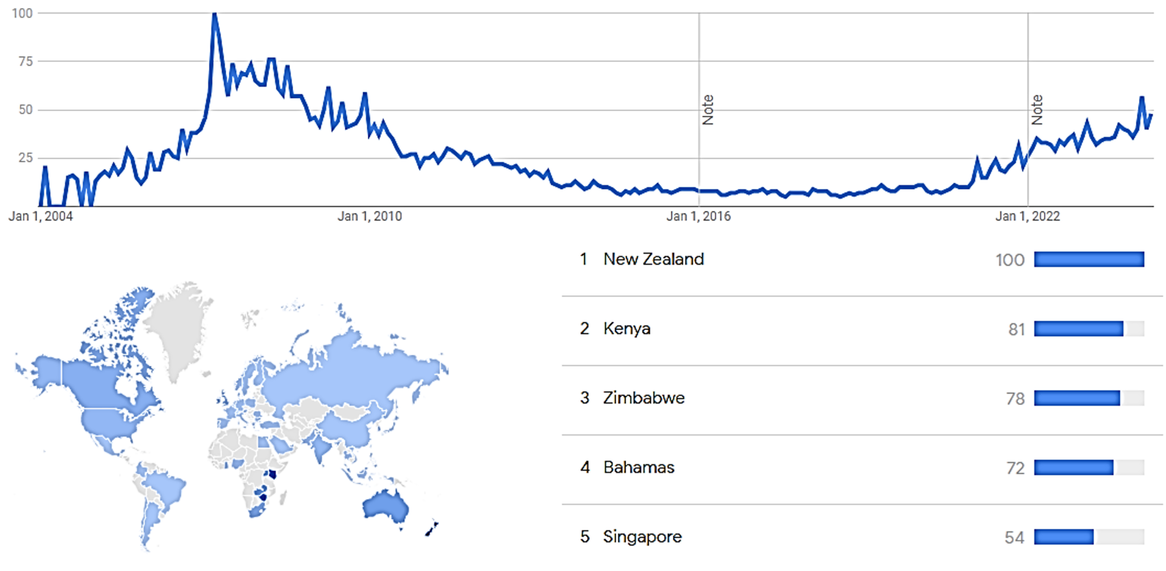


Figure 7: Google Trends results for the keyword "carbon credits"

Furthermore, an analysis of Google Trends data revealed an intricate landscape at the intersection of carbon credits and ICTs, notably reflecting broader market dynamics, corporate initiatives, and individual interest in climate action. While searches for terms like 'carbon footprint reduction,' 'investment in carbon credits,' and 'carbon credit market' demonstrated notable peaks, searches for specific carbon credit-related queries like 'what are carbon credits' and 'buy carbon credits' exhibited consistent interest over time. This pattern suggests a multifaceted approach to carbon credit exploration, with individuals and entities seeking information on carbon offsetting strategies, investment opportunities, and market trends. Moreover, the prominence of queries related to corporate involvement and investment signals a growing recognition among businesses of the importance of carbon credits in their sustainability initiatives and environmental stewardship efforts. These trends underscore the evolving carbon credit awareness and adoption landscape, shaped by diverse stakeholder interests and market dynamics."

4.4 Environmental Integrity

CCs advance sustainable development objectives by integrating environmental, social, and economic considerations in emission reduction projects and fostering a transition to a more sustainable, low-carbon future. So, as the authors mention [10], it is important to implement and monitor carbon credits using robust standards and methodologies to guarantee their environmental integrity and maximize their sustainable development impact. Projects must adhere to recognized standards, establishing rigorous criteria for project evaluation, emission reductions, and sustainable development co-benefits[11].

1° Clean Development Mechanism (CDM)[12, 13]: The Clean Development Mechanism is one of the flexible mechanisms established under the United Nations Framework Convention on Climate Change (UNFCCC). It allows developed countries to invest in emission reduction projects in developing countries and receive Certified Emission Reductions (CERs) as carbon credits.

The CDM projects undergo a rigorous approval process and must demonstrate that the emission reductions achieved are in addition to what would have occurred without the project. It focuses on sustainable development, and projects must contribute to the host country's sustainable development goals.

2° Verified Carbon Standard (VCS)[14, 15]: The Verified Carbon Standard is a leading voluntary greenhouse gas program and certification standard. It provides guidelines and requirements for developing, quantifying, and verifying carbon offset projects. VCS projects can be implemented globally and cover various sectors, including renewable energy, forestry, agriculture, and waste management. It ensures that projects meet specific criteria to ensure the credibility and accuracy of the emission reductions achieved.

3° Gold Standard [16, 17, 18]: The Gold Standard is another widely recognized certification standard for carbon offset projects. It was initially developed in collaboration with WWF and is managed by the Gold Standard Foundation. It focuses on projects that deliver sustainable development benefits and reduce greenhouse gas emissions. Projects must demonstrate their contributions to poverty reduction, health improvements, and environmental sustainability. It covers sectors such as renewable energy, energy efficiency, afforestation, and clean cookstoves.

4.5 Benefits and challenges

By investing in CCs, companies can simultaneously address environmental damage, meet regulatory requirements, enhance their reputation, and capitalize on business opportunities. It's a strategic and tangible way for companies to demonstrate their commitment to sustainability, reduce their environmental impact, and contribute to the transition to a low-carbon economy. However, several challenges and impediments exist that can hinder their effective implementation.

Fig. 8 contrasts the advantages and hardships of CC, prioritizing the most relevant and challenging ones in the short term (in dark blue). In the lightest blue, located down, are consequential benefits and medium-term challenges that could occur after satisfying the former. The dotted arrows that read as 'require' identify the importance of its implementation.

The principal tangible benefit of CCs is that it allows companies to take immediate action to offset or reduce their greenhouse gas emissions. This demonstrates their commitment to addressing climate change and meeting sustainability goals. It can help companies align with global emission reduction targets, such as the Paris Agreement, and showcase their environmental responsibility. Many jurisdictions have implemented regulations or mandatory reporting frameworks requiring companies to measure and reduce carbon emissions. Investing in carbon credits can assist companies in meeting these regulatory obligations by offsetting their emissions and demonstrating compliance with emission reduction targets [19]. Taking proactive steps to reduce carbon emissions and investing in carbon credits can enhance a company's reputation and brand image. It demonstrates environmental leadership and can attract environmentally conscious customers, investors, and partners. It enhances stakeholder engagement and fosters positive relationships with regulators, communities, and NGOs.

On the other hand, determining the accurate measurement of emissions reductions and ensuring their verification can be complex and costly. Establishing reliable methodologies, monitoring systems, and independent verification processes requires technical expertise and robust standards[20]. Ensuring transparency and consistency across different projects and regions can be challenging. The existence of multiple carbon credit standards and methodologies can create confusion and inconsistency. Harmonizing and aligning these standards is essential for ensuring the integrity and credibility of carbon credits. Robust quality assurance mechanisms are needed to prevent fraud and double counting and ensure that credits represent real and permanent emission reductions[4]. Establishing additionality, which means demonstrating that emissions reductions are additional to what would have occurred without the project, can be subjective and difficult. Determining the baseline against

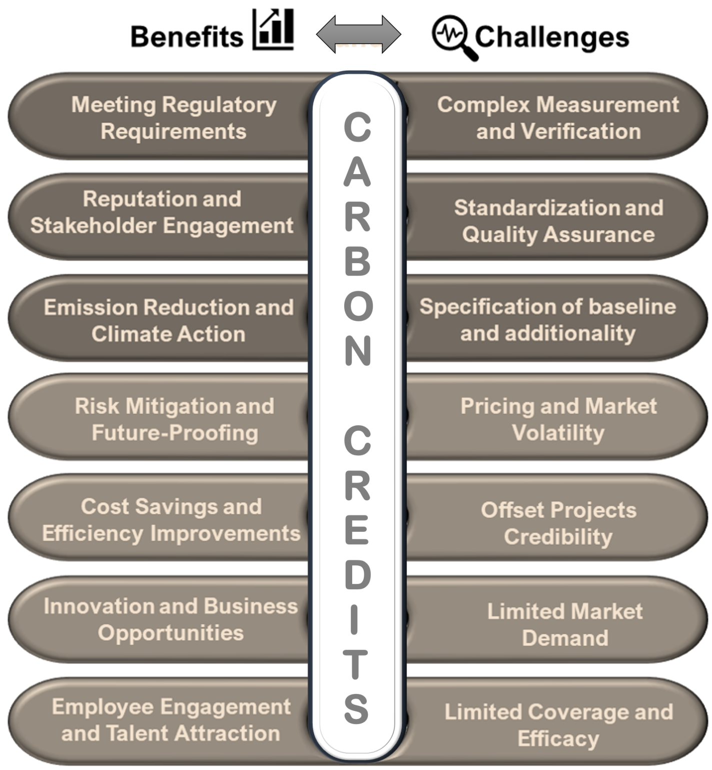


Figure 8: Benefits vs. Challenges of CCs.

which emissions reductions are measured requires rigorous analysis and careful consideration of counterfactual scenarios.

4.6 ICTs Perspectives

The following compilation of ICT perspectives represents a synthesis of ideas extracted from the review, highlighting the diverse ways in which information and communication technologies (ICTs) contribute to the carbon credit ecosystem. ICTs play a significant role in facilitating and enhancing various aspects of carbon credit projects, including data management, decision-making, and collaboration. By leveraging advanced technological tools and platforms, carbon credit initiatives can achieve greater efficiency, transparency, and impact, advancing global climate change mitigation efforts. The following list elucidates key ICT perspectives identified in the review, shedding light on their potential applications and implications for advancing carbon credit projects.

– Monitoring and Measurement: Technology, including remote sensing, satellite imagery, and geospatial data, is pivotal in enabling accurate and efficient monitoring of emissions, land-use changes, and project activities within carbon credit projects [21]. By harnessing these advanced monitoring technologies, project managers can assess baseline emissions, track progress, and verify emission reductions with greater precision and reliability. Remote sensing and satellite imagery provide comprehensive coverage and real-time data, allowing for continuous monitoring of project sites and surrounding landscapes. Geospatial data analysis further enhances monitoring capabilities by facilitating the identification of emission hotspots, land-use changes, and ecosystem impacts [12]. Moreover, these technologies contribute to the transparency and credibility of carbon credit projects by providing verifiable evidence of emission reductions and project activities. By integrating technology-driven monitoring and measurement solutions, carbon credit projects can enhance their environmental integrity, mitigate risks, and maximize their contribution to climate change mitigation efforts.

– Data Management and Analysis: Technology is critical in facilitating collecting, storing, and analyzing large volumes of data generated by carbon credit projects [22]. This includes data on emissions, project performance, and associated co-benefits. Advanced data management systems leverage cloud computing and distributed databases to store and organize this information efficiently, ensuring accessibility and scalability as project datasets grow [23]. Furthermore, sophisticated data analytics tools and algorithms enable the processing and analysis of this data, extracting actionable insights and supporting informed decision-making. By identifying trends, patterns, and correlations within the data, these tools enhance project monitoring and evaluation, enabling stakeholders to assess project effectiveness, optimize resource allocation, and maximize environmental impact. By integrating technology-driven data management and analysis solutions, carbon credit projects can unlock new opportunities for innovation, efficiency, and sustainability in the fight against climate change.

– Decentralization and Transparency: Blockchain technology presents compelling opportunities to enhance transparency and traceability in the carbon credit market [24]. By leveraging decentralized ledger technology, blockchain provides a secure and immutable platform for recording and verifying transactions, ensuring the integrity and authenticity of carbon credits [25]. This decentralized approach minimizes the risk of fraud, double counting, and manipulation, fostering trust among market participants and regulatory bodies [26]. Furthermore, blockchain streamlines processes related to issuing, transferring, and retiring carbon credits, reducing administrative burdens and transaction costs. For example, case studies have shown blockchain implementation for traceability applications, such as the origin coffee supply chain traceability [27] and a Blockchain-based approach to support an ISO 9001:2015 Quality Management System [28]. Through its transparent and auditable nature, blockchain technology enhances market efficiency, accelerates climate action, and promotes greater accountability in the global effort to combat climate change.

– Digital Platforms and Marketplaces: digital platforms and marketplaces play a critical role in accelerating the transition to a low-carbon economy by facilitating the efficient exchange of carbon credits and driving investment in emission reduction projects [29]. These innovative platforms serve as centralized hubs that connect buyers and sellers, streamline transactions, and facilitate carbon credits' certification and registration processes. These platforms enhance carbon credit trading's transparency, security, and efficiency by leveraging digital technologies, such as blockchain and smart contracts [30]. Moreover, digital marketplaces offer diverse project options, providing buyers with access to a broader portfolio of carbon credit opportunities. This increased market liquidity fosters competition and innovation, driving down transaction costs and expanding participation in carbon credit markets [31].

– Internet of Things (IoT): IoT devices and sensors play a crucial role in modern carbon credit projects, offering real-time data collection capabilities for energy consumption, emissions, and project performance, as several authors suggest [21], [32], [33]. Project managers can access continuous monitoring and data analytics by deploying IoT devices and sensors, enabling informed decision-making and proactive management of project activities. These technologies facilitate automated reporting and empower project stakeholders to optimize energy systems and resource utilization in real-time [34]. Additionally, IoT technology enhances project efficiency by providing insights into operational processes and identifying opportunities for improvement. Furthermore, integrating IoT devices and sensors ensures compliance with project requirements and regulatory standards, contributing to carbon credit initiatives' environmental integrity and credibility.

– Modeling and Scenario Analysis: Technology-enabled modeling tools and scenario analysis are instrumental in evaluating carbon credit projects' potential impact and viability [35]. These sophisticated tools leverage advanced algorithms and data analytics to simulate various scenarios, estimate emission reductions, and assess project feasibility [36]. By providing a virtual environment for exploring different project configurations and parameters, these tools enable project managers to identify optimal designs, evaluate risks, and make informed decisions regarding project selection and investment [37]. By harnessing the power of technology-driven simulations, carbon credit projects can optimize outcomes, mitigate risks, and maximize their contribution to climate change mitigation efforts.

Technology is an indispensable catalyst in successfully implementing carbon credits, playing a pivotal role across every stage of their lifecycle. From accurate measurement and monitoring of emissions to ensuring transparency, traceability, and efficiency in market transactions, technology is the linchpin that enables the effectiveness and credibility of carbon credit mechanisms. It empowers accurate data collection and analysis, enabling robust measurement of emission reductions and project performance. Cutting-edge remote sensing, satellite imagery, and data analytics tools allow real-time emissions tracking and verification of project outcomes. This data-driven approach enhances the accuracy of carbon credit calculations and bolsters confidence in the environmental integrity of the credits.

5 Conclusion

This paper provided an overview of the carbon credit (CC) markets. According to the evidence, this mechanism is a powerful alternative to mitigate global greenhouse gas emissions. It presents an opportunity to accelerate the deployment of essential strategies, including renewable energy implementation, energy efficiency improvements, reforestation, and carbon sequestration projects. However, as an emerging market, it faces significant challenges such as regulation, standardization, measurement, verification, remuneration, and establishing trust to promote investment.

It is crucial to approach carbon credits with careful consideration. Challenges such as potential price volatility, concerns about environmental integrity, and the need for harmonized standards should be acknowledged. Nevertheless, ongoing research, technological advancements, and improved governance mechanisms are addressing these issues, enhancing the credibility and effectiveness of carbon credit markets.

One potential approach to overcome these challenges is through technology adaptation. The development of the carbon credit market, coupled with the utilization of blockchain and the Internet of Things (IoT), can offer solutions for monitoring, management, standardization, verification, and market transparency, ultimately leading to the consolidation and growth of this market.

The review of the state of the art demonstrated the carbon credit market's interdisciplinary nature and widespread impact. Lines of research focused on political, economic, environmental, and technological aspects were identified. While there is a growing interest among authors and scientific journals in exploring the opportunities of these emerging markets, concerted efforts from the private sector to generate investment and market development and the public sector to promote regulation and legislation are essential for market consolidation.

Ultimately, climate change continues to pose challenges to the development of economies at an accelerating pace. Therefore, the commitment of all stakeholders must be strengthened to rapidly and efficiently deploy such strategies to ensure the sustainable development of the economy and society.

Competing Interests

The authors expressly declare that they have no conflicts of interest.

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