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Exploring the scientific literature on clean development mechanisms: A bibliometric analysis

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A R T I C L E I N F O

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A B S T R A C T

The Clean Development Mechanism (CDM) was established under Article 12 of the Kyoto Protocol to assist developed countries in reducing greenhouse gas (GHG) emissions by transferring technologies to developing countries and creating a carbon credit market. Despite playing a crucial role in reducing GHG emissions, the CDM faced market uncertainties, inadequate targets for GHG reduction among signatory countries, political and institutional obstacles that led to a decline in CDM projects after 2012. Currently, China, India, and Brazil have the highest percentage of registered CDM projects. The literature presents both evidence in favor of and against CDM projects. To evaluate the evolution and updates in the literature, a bibliometric analysis of 810 articles published between 1998 and 2021 was conducted. The USA had the highest number of published articles, followed by Germany and China, with Energy Policy and Climate Policy as the main journals for disseminating the topic. The study identified four main research axes that expanded into seven thematic groups. Additionally, the evolution of four lines of interest was evident over time, starting with the greenhouse effect and Kyoto Protocol, followed by economic and business aspects, sustainable development and energy policy, and finally, technological transfer and innovation.

1. Introduction

The consumption of products has led to a proportional increase in waste disposal, resulting in environmental imbalances. In response, many countries leaders have discussed sustainable development strategies that can achieve economic growth without compromising the environment for future generations. The Brundtland Commission report of 1987 defined sustainable development (SD) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). Ten years later, the Kyoto Protocol marked an international effort to address climate change, sustainable development, and multilateral cooperation. The 1998 report outlined three mechanisms for cooperation between countries: Joint Implementation (JI), described in Article 06 of the protocol; Clean Development Mechanisms (CDM), described in Article 12; and Emissions Trading (ET), outlined in Article 17 of the report (UNFCCC, 1998).

The Kyoto Protocol categorized nations into two groups: developed nations listed in Annex B of the Protocol, and developing nations referred to as non-Annex B (UNFCCC, 1998). However, over time, this classification was revised to Annex-I and non-Annex I nations, respectively (UNFCCC, 2018a,b). The KP's mechanisms, particularly the Clean Development Mechanism (CDM), aim to reduce Greenhouse Gas (GHG) emissions through investment and technology transfer between developed and developing countries. The CDM allows Annex-I countries to achieve GHG emission reduction commitments by taking advantage of low-cost emission reductions outside their territories (UNFCCC, 2008). Since climate change mitigation does not depend on to the specific location of emission reductions, a reasonable economic approach is to minimizing emissions to their lowest achievable level everywhere (Cansino et al., 2022).

The resulting GHG emission reductions from CDM projects can be converted into Certified Emission Reductions (CERs) or Carbon Credits, which Annex-I nations can purchase. According to Zhang et al. (2018), the CDM encourages sustainability in developing countries (CDM host countries) by selling CERs obtained from GHG mitigation projects to developed countries (CDM investment countries).

As outlined in Article 3 of the Protocol, parties committed to reducing global GHG emissions by 5% compared to 1990 levels between 2008 and 2012 (UNFCCC, 1998). The Protocol came into effect in 2005

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(UNFCCC, 2004), and countries had the period of 2005–2008 to prepare themselves for meeting their GHG reduction targets in the following years. However, despite the three-year preparation and five-year goal fulfillment period, it turned out to be insufficient. In 2012, at the 18th Conference of the Parties (COP18) held in Doha (Qatar), the countries adopted the "Doha Amendment to the Kyoto Protocol," which established a second commitment period for GHG emission reduction from January 2013 to December 2020 (UNFCCC, 2012a). However, according to Massetti (2014), only the European Union and Australia had committed to emissions reduction targets from 2013 to 2020, while Canada, Japan, and Russia had withdrawn from the treaty.

In 2015, the Paris Agreement was signed, which set reduction targets for the post-2020 period, adopting five-year cycles aimed at limiting global warming to below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels. The Paris Agreement applied to all signatory countries of the Climate Convention (UNFCCC, 2015b), unlike the Kyoto Protocol, which only set mandatory reduction targets for developed countries (UNFCCC, 2015a; Serrano and Mir, 2021). Mele et al. (2020) suggest that the CDM had a positive impact, particularly on renewable energy projects, which stimulated political actions for environmental sustainability.

However, there are several challenges to achieving these goals, with one significant hurdle being the carbon price in USD/tCO_2eq. According to Timilsina (2009) and Lin and Jia (2019), this cost serves as an economic barrier. Although initiatives worldwide generated US$53 billion in revenues in 2020, an increase of about US$8 billion compared to 2019, they only covered 21.7% of global GHG emissions, as reported by the World Bank in 2020. The bank also noted that global average carbon prices remain well below the range of USD 40–80/tCO_2eq necessary to meet the Paris Agreement's temperature target of 2 °C. Only 3.76% of global emissions have a carbon price in this range or higher. The World Bank estimates that even higher prices will be necessary during the next decade to meet the 1.5 °C target (WorldBank, 2021).

The CDM has played a significant role in international carbon trading due to its scale. The European Union Emissions Trading System (EU-ETS), which was established in 2005, serves as the commercial foundation of carbon credits (Vlachou and Pantelias, 2017).

The first CDM project was registered in Brazil in November 2004, and from 2004 to 2012, the number of registered projects grew exponentially before declining. In the historical series analyzed, 7845 projects were registered, of which 4672 were long-term projects with the capacity to reduce 930 GtCO_2eq per year, and 3173 were short-term projects with the capacity to reduce 84 GtCO_2eq per year. The ten countries with the most registered CDM projects, representing 87.67% of all registered projects, are China (3763; 47.97%), India (1685; 31.48%), Brazil (344; 4.38%), Vietnam (258; 3.29%), Mexico (192; 2.45%), Indonesia (148; 1.89%), Thailand (144; 1.84%), Malaysia (143; 1.82%), Chile (111; 1.41%), and the Republic of Korea (90; 1.15%) (UNFCCC, 2021).

Fig. 1 depicts the annual evolution of the number of CDM projects. Between 2004 and 2012, there was an annual average of 794 registered projects. However, after 2012, there was a significant drop in the number of registrations, with an annual average of 87 registered projects between 2013 and 2020. In 2020, only 27 projects were registered.

This sudden decline was motivated by several factors, including the effects of the 2008 economic crisis (WorldBank, 2020; 2021), as well as the lack of clear GHG reduction targets following the failure of the Copenhagen Conference in 2009 (COP 15) (Cantore, 2011). This generated uncertainty about the future of international climate policy, which, coupled with delays in project validation, discouraged carbon trading and reduced the price of this commodity (Michaelowa and Buen, 2012).

Furthermore, there was a lack of demand for emission credits during the period 2013–2020, caused by timid emission reduction targets and increasing barriers to the import of credits. As a result, the price of emission credits collapsed, leading to a loss of confidence in the long-term stability of market mechanisms and their incentives for mitigation. This undermined the human capacity to deal with these issues and significantly shook confidence in the long-term effectiveness of market-based mechanisms (Delbosc et al., 2011; Michaelowa, 2015).

In this context, there has been much debate about the effectiveness of these instruments. For example, Geres and Michaelwa (2002) highlight the importance of evaluating indirect effects on baseline development that calculates CO_2eq reductions for CDM and JI projects. As a result, the literature presents evidence both for and against CDM projects. Sharifi et al. (2021) have shown that climate research has evolved significantly in recent years, particularly after 2015, with major topics including institutional mechanisms for climate policies, conflicts and violence, migration and adaptation, resource management, energy, and environmental security. However, Bumpus and Cole (2010) question the transparency of CDM information and suggest that it does not contribute much to academic research on the topic because of its focus on the carbon market. Therefore, a more thorough investigation of the scientific position on the subject is necessary, particularly regarding the

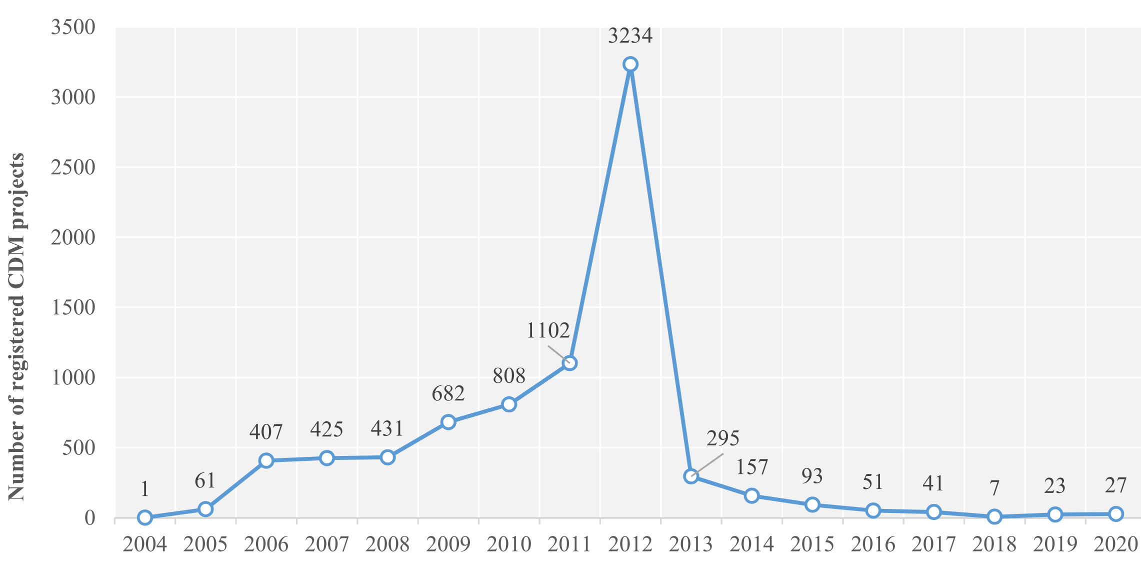

Fig. 1. Number of registered CDM projects through of the years.

aspects of the Triple Bottom Line (TBL).

Starting at the institutional and environmental level, Brooks et al. (2005) presented 11 vulnerability indicators for countries to adapt to climate risks, including political rights and the effectiveness of the government, which play a crucial role in decision-making. However, Charman (2008) emphasizes that CDM is not just an environmental project but also comes with political complications that can directly affect the economies of emerging countries, leading to many complications that can ultimately doom the Kyoto mechanisms to failure. Similarly, Hultman et al. (2009) argue that while CDM stimulates a large number of projects, it has a geographically uneven distribution dominated by certain sectors, and large-scale projects bring few direct benefits to the local population, making the mechanism flawed and falling short of its goal.

On a more positive note, Shi et al. (2021) demonstrate that CDM projects have effectively reduced carbon dioxide emissions per unit of gross domestic product (GDP), as well as the growth rate of carbon dioxide emissions in China. According to Cui et al. (2020), CDM projects have also contributed to business innovation in renewable energy and energy efficiency. The authors suggest that the more energy-intensive the industry, the greater the potential impacts that companies could absorb from CDM projects. Additionally, Kallbekken (2011) argues that, with appropriate accounting and under realistic assumptions, CDM has the potential to reduce carbon leakage by over 50%, making it the most effective way to reduce emission abatement costs in Annex-I Countries.

argue that the focus on deriving economic benefits from Clean Development Mechanism (CDM) investments has led developing countries to become more competitive, but has not prioritized broader sustainable development goals. As a result, the long-term benefits of CDM projects and increased public participation from local stakeholders have often been overlooked. Meanwhile, Yue et al. (2020) highlight the crucial role of sustainable energy generation in achieving sustainable development, projecting the most efficient decarbonization technologies using a marginal cost model for 2050. The paper also identifies the sectors with the highest potential for reducing CO_2 emissions, with transport being the most affected.

Since the establishment of Clean Development Mechanisms (CDMs) in the Kyoto Protocol, numerous studies have explored the associated risks, with transaction costs emerging as a key concern for investors. Scholars such as Woerdman (2001), Michaelowa et al. (2003), Krey (2005), Chadwick (2006), Torres et al. (2010), Galik et al. (2012), and Honlonkou and Hassan (2015) have identified these costs as the primary obstacle to attracting private investors and project developers. Additionally, Michaelowa and Jotzo (2005) have emphasized that transaction costs and institutional rigidity are limiting factors for the implementation of Kyoto mechanisms, in comparison to more straightforward domestic measures for reducing greenhouse gas emissions. Echoing this view, Pearson (2007) underscores that CDMs represent a market rather than a development fund or a mechanism for promoting renewable energy.

Despite the potential financial benefits of Clean Development Mechanism (CDM) projects, Cormier and Bellassen (2013) demonstrate that a significant proportion (69%) of these projects fail due to problems or incompatibilities encountered during the validation stage. The authors also note that only 31% of Certified Emission Reductions (CERs) were issued in a timely and optimal manner, with 39% being issued later than expected, primarily due to delays in the approval process. Additionally, 30% of CERs will never be issued due to design flaws. Cormier and Bellassen identify technology as a critical factor in project risks. Wu et al. (2020) argue that the carbon trading market has been unstable, with falling prices, transaction inactivity, and recession. The authors attribute the decline in the future price of CERs to two factors: fluctuations in the foreign exchange market, closely linked to currency liquidity, and volatility in coal prices in energy markets. Other studies have highlighted the importance of technology transfer between developed and developing countries in the success of CDM projects for reducing greenhouse gas emissions and promoting economic growth (Parikh, 2000; Haites et al., 2006; Dechezleprêtre et al., 2008; Hascic et al., 2011; Schmid, 2012; Simon et al., 2017).

In the social realm, Crowe (2013) attempts to identify specific characteristics of projects that are beneficial to vulnerable populations. The author reports that while "regular" CDM projects (focused on climate) have moderate success in delivering benefits to the poor, projects registered as "community and biodiversity" have a better track record of delivering such benefits. Consequently, most projects still prioritize the environmental and economic pillars, with little progress made in the social pillar of the Triple Bottom Line (TBL). In the political realm, Li and Lin (2021) highlight that a host country's affluence, experience with international trade, interest in energy, and the cost of reducing carbon emissions are key factors in determining the number of CDM projects installed. The political, legal, and cultural environment can also influence the decision to implement a new CDM project.

Therefore, given the creation, development, and decline of CDM projects, as well as existing research pointing out their effectiveness and limitations, understanding these mechanisms becomes critical. Analyzing the literature's structure on the subject could improve tools to fight climate change.

Thus, this paper aims to analyze relevant scientific research on Clean Development Mechanisms to answer the following research questions:

- RQ1: How has the scientific research on Clean Development Mechanisms (CDM) evolved since the publication of the Kyoto Protocol?
- RQ2: Who are the major contributors (e.g., journals, authors, and countries) to the CDM literature?
- RQ3: Which studies are considered to be key in the scientific literature on CDM?
- RQ4: What are the primary thematic areas that emerge from the scientific literature on CDM?

2. Research methods

Informetrics is an interdisciplinary field that encompasses all studies and metrics related to the science of information (Egghe, 2005). The term "Informetrics" was introduced by Blackert and Siegel (1979) and Nacke (1979), but gained more prominence with the works of Egghe and Rousseau (1988, 1990). However, the concept of Informetrics was already present in the studies of Lotka (1926), Bradford (1934), and Zipf (1949).

Bibliometrics, a term coined by Pritchard (1969), is a subfield of Informetrics that emphasizes the quantitative and statistical aspect of information analysis. Bibliometrics has become increasingly important in recent years due to its ability to synthesize information and its intersection with Scientometrics. This intersection allows for the analysis of the evolution of sciences, their relationships, and trends. Bibliometrics provides a diagnosis of authors, journals, and institutions that work in a particular field and serves as a support for measuring technical performance to determine academic productivity (Narin et al., 1994; Vinkler, 2010).

This paper is a bibliometric study on Clean Development Mechanisms (CDMs) and uses the scientific and indexing databases Web of Science (WoS) and Scopus (SCP) to understand the evolution of publications by year, publications by countries, reference institutions, collaboration networks between countries and authors, in addition to mapping the research trend in this field.

Zupic and Cater (2015) propose five steps to carry out a bibliometric study, and this paper followed these steps, as shown in Fig. 2.

Using a PRISMA methodology (Page et al., 2021) for selecting papers, 810 documents were aggregated for analysis. This research only used papers published after 1997 since CDM projects were instituted only after that year. Additionally, only papers were used in the analysis, and books, book chapters, or abstracts were excluded from the final analysis. For quantitative calculations, the R software (Team, 2013) was

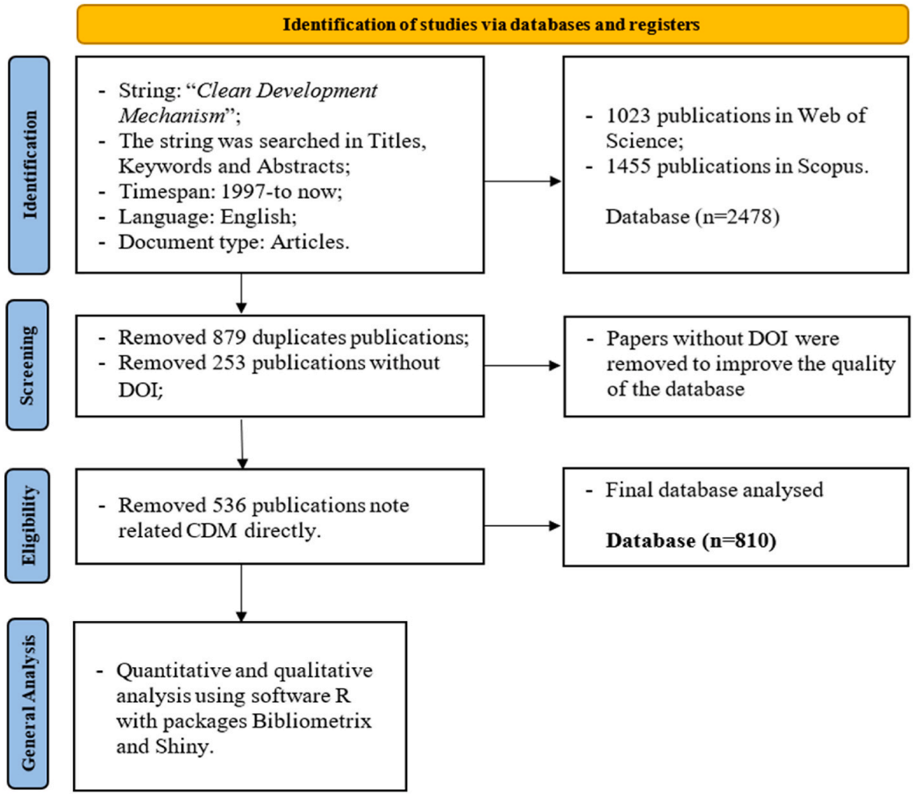

Fig. 2. Detailed flowchart of the research methodology.

used, set in RStudio with the Bibliometrix package (Aria and Cuccurullo, 2017) with Shiny mechanism support (Chang et al., 2017).

It is important to highlight that currently there are many software packages that could have been used in quantitative analysis. As an example, we can mention VosViewer, initially proposed by Van Eck and Waltman (2010), which has strong points such as the ability to construct and visualize bibliographic maps, heavily relying on co-citation frequencies (offering tools like density view and cluster density view), besides being user-friendly.

Another widely used software is CitNetExplorer, introduced by Van Eck and Waltman (2014), which exhibits a strong capability to analyze and visualize citation networks, particularly through clustering approaches and a combination of keyword-based citation expansion.

However, the choice was made for RStudio with the Bibliometrix package due to its ability to easily combine Web of Science and Scopus databases and provide excellent analysis tools. Some of these tools are similar to those of the previously mentioned software, while others are unique, such as tracking the evolution of the most frequent terms over time.

3. Results

This section presents the results of the bibliometric analysis, which aims to identify the patterns of studies related to CDM projects, their temporal evolution, prominent authors and institutions, and academic trends in this field.

3.1. Publications per year

The content of this section aims to answer the first research question (RQ1) of this work. In this sense, a total of 810 papers published between 1998 and 2021 were analyzed, and Table 1 provides a summary of the analyzed database. The temporal evolution of the number of published papers and citations per year can be observed in Fig. 3.

Table 1
Summary of database.

Metric	Value
Timespan	1998:2021
Sources	276
Papers	810
Average citations per paper	18.29
Average citations per year per paper	1.649
References	26,084

It can be noted that the peak of studies in this field was reached in 2009 (69 papers) and 2013 (71 papers). After 2013, there was a decrease in the number of papers published, coinciding with the drop in the number of registered CDM projects, as shown in Fig. 1. The number of citations per year follows the same trend, indicating less academic interest after 2013. The uncertainties generated by the failed negotiations at COP 15/Copenhagen and COP 16/Cancún (Campbell and Klaes, 2011) contributed to this decrease in interest. At COP 17/Durban in 2011, 194 countries committed to renewing the Kyoto Protocol and preparing a global pact to come into force in 2020 (UNFCCC, 2012b). However, the uncertainty surrounding the Kyoto mechanisms caused countries to reduce their investment in these projects, which led to fewer case studies available for investigation of the phenomena involved with their applications.

It is evident that the theme lost strength both in practical and academic spheres after the completion of the first stage of the Kyoto Protocol (1997–2012) and the beginning of the second stage (2013 – to now), as depicted in Fig. 4. The average number of citations per year decreased from 24.09 to 9.68, indicating a reduction of 59.82%. It is important to note that there is a considerable time difference between the two periods, but the decrease in interest regarding the theme after 2013 is still noticeable.

This behavior seems to reflect a decline in interest in the topic by

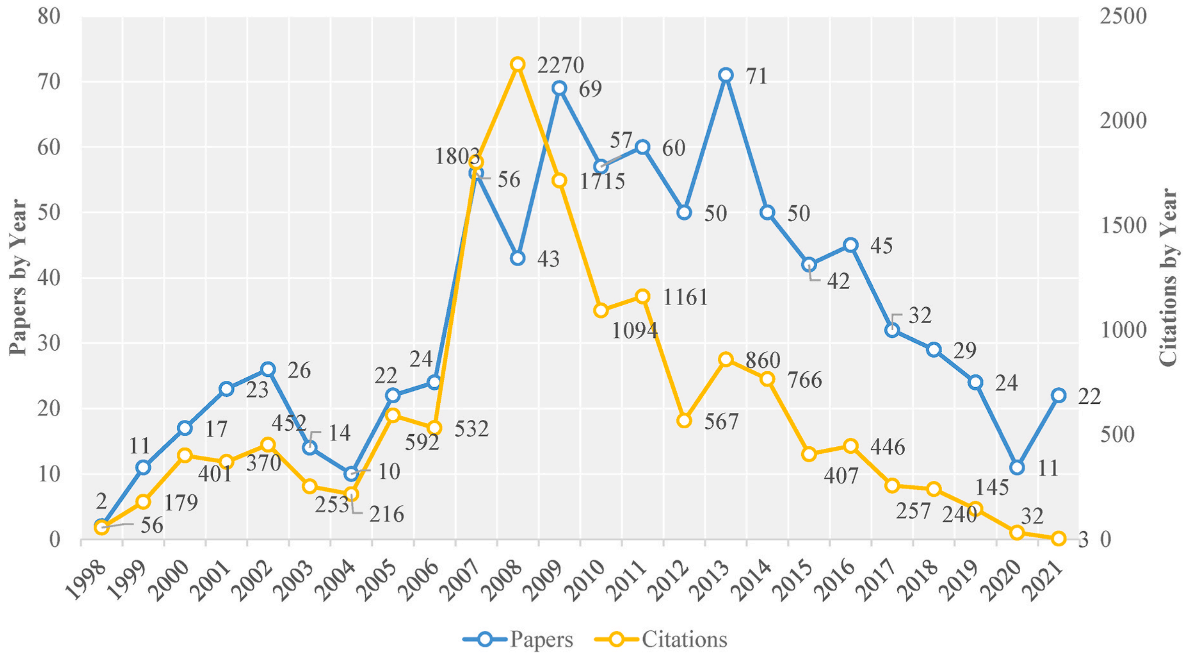

Fig. 3. Papers and citations evolution in CDM through of the years.

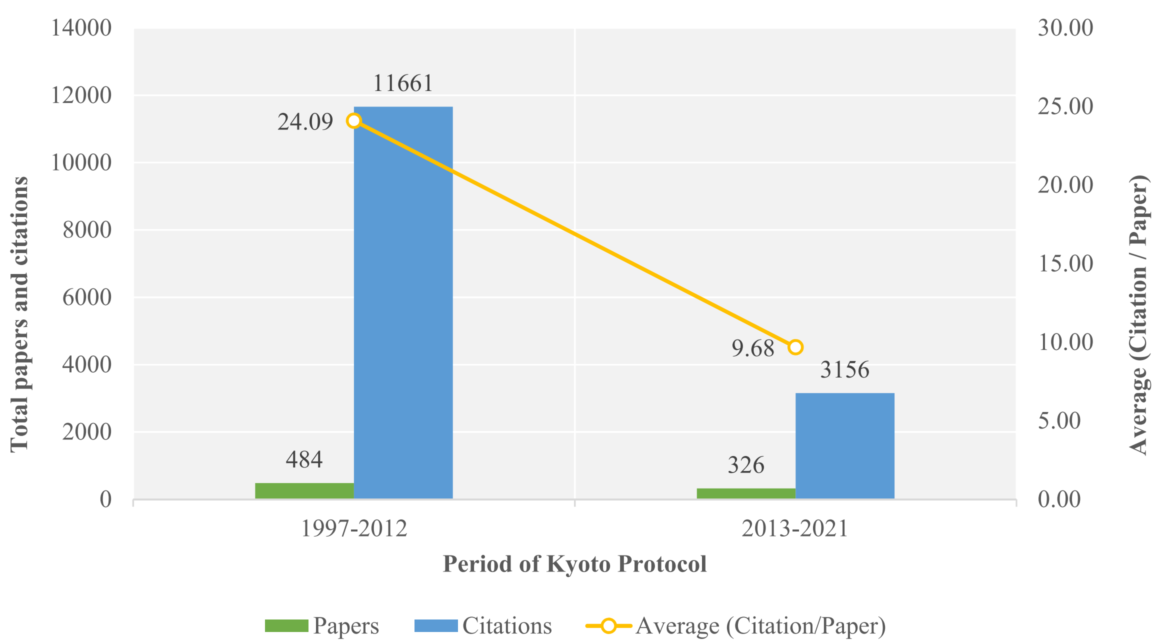

Fig. 4. Cumulative papers and citations by period of Kyoto Protocol.

academia starting from the year 2013. However, it should be considered that there was a significant reduction in the implementation of these projects from this year, partly due to the low market value of CERs and also due to changes in UNFCCC regulations on these projects, which reduced their attractiveness. This certainly had an impact on the scientific production on the subject since then.

3.2. Major contributors

In this section, we explore the information regarding the most prominent contributors to CDM scientific literature (RQ2). The aim is to present a comprehensive overview of the authors, key scientific journals, and countries that are actively involved in producing research on this subject, as illustrated in Table 2.

Table 2 presents a ranking of the 15 authors with the highest number of publications, ranked by the number of citations. Additionally, it is noteworthy to highlight authors with many citations but fewer published articles, such as Antônio Trabucco (689 citations, 3 papers), Diana M. Liverman (563 citations, 4 papers), Robert J. Zomer and Deborah A. Bossio (553 citations, 1 paper), and Adam G. Bumpus (502 citations, 3 papers).

The influence of Axel Michaelowa is particularly noticeable among the most cited authors, which can be observed more clearly in the co-citation network (Fig. 5). Co-citation analysis seeks to identify the

Table 2
Ranking of 15 most widely cited authors.

Ranking	Authors	Citations	Papers	Citation/ Paper	Paper/ Year
1	Michaelowa, Axel	844	29	29.10	3.45
2	Olsen, Karen H.	371	7	53.00	4.11
3	Boyd, Emily	348	6	58.00	6.50
4	Corbera, Esteve	304	7	43.43	6.04
5	Purohit, Pallav	252	9	28.00	4.65
6	Cole, John C.	214	6	35.67	4.30
7	Newell, Peter	205	8	25.63	3.87
8	Karakosta, Charikleia	183	13	14.08	2.30
9	Psarras, John	162	13	12.46	1.66
10	Flamos, Alexandros	124	6	20.67	2.43
11	Doukas, Haris	118	8	14.75	1.53
12	Lazarus, Michael	84	6	14.00	1.79
13	Rahman, Shaikh M.	65	6	10.83	1.71
14	Bayer, Patrick	42	6	7.00	1.24
15	Paulino, S nia	13	6	2.17	0.75

influence between authors, articles, or sources using similarity measures (McCain, 1990; Zupic and Cater, 2015).

Fig. 5 illustrates the four major co-citation clusters between authors, their partnerships, and lines of research. These clusters are strongly influenced by international agencies such as the UNFCCC (United Nations Framework Convention on Climate Change), IPCC (Intergovernmental Panel on Climate Change), WB (World Bank), and OECD (Organisation for Economic Co-operation and Development), as well as by authors with the most cited articles in that group, such as Philip M. Fearnside, 1999a,b) and Zhong Xiang Zhang (2006).

The first cluster (red) mainly discusses the effects of climate change and the Kyoto Protocol. The second cluster (blue) focuses on the implementation and dynamics of CDM projects, additionality, energy efficiency, and the main authors include Axel Michaelowa (Michaelowa and Jotzo, 2005), Jane Ellis (Ellis et al., 2007), and Malte Schneider (Schneider et al., 2008). The third cluster (green), with main authors Antoine Dechezleprêtre (Dechezleprêtre et al., 2008), Erick Haites (Haites et al., 2006), and Stephen Seres (Seres et al., 2009), emphasizes transaction costs and technology transfer provided by the partnership of countries in CDM projects. Finally, cluster four (purple) comprises studies on the dichotomy between Sustainable Development and GHG emission reduction, with contributions from Karen Holm Olsen (2007), Christoph Sutter (Sutter and Parreño, 2007), and Emily Boyd (Boyd et al., 2009).

In regards to the main scientific journals, Table 3 presents the 15 considered most relevant in terms of number of publications and citations.

Starting with the analysis of the main academic sources, Table 3 and Fig. 7 were created based on the 15 most relevant journals. From this data, it is evident that the journal Energy Policy has the highest representation in terms of number of publications and citations. Following Energy Policy, Climate Policy has a great influence, followed by Agriculture Ecosystems and Environment, Climatic Change, and Economic Geography.

It is also important to highlight that Economic Geography has the highest average citations per article, and the second highest impact factors, while the journal Trends in Ecology and Evolution has the second highest average citations per article and the highest impact factor among the most relevant publications on the topic.

Another important aspect to be observed is the relationships among the scientific sources, which are presented in Fig. 6. The first cluster (red) is focused on the supply and use of energy with social and environmental aspects, as well as discussions on Sustainable Development, with the debate centered on Energy Policy, Journal of Cleaner Production, and Renewable Energy. Cluster 2 (green), on the other hand, is focused on the discussion of climate policies, particularly on issues of adaptation and mitigation of risks involved, and also has a strong role in discussions of the environment and forests, with a focus on Climate Policy and Climate Change journals. Finally, the third cluster (blue) discusses the relationships between climate change and the economy, promoting the debate focused on the social justice of sustainability, where the discussion is more decentralized, in journals such as Ecological Economics, Environmental and Resource Economics, Energy Economics, and others.

Another relevant characteristic to be analyzed in this section is the countries participation and collaboration in this theme.

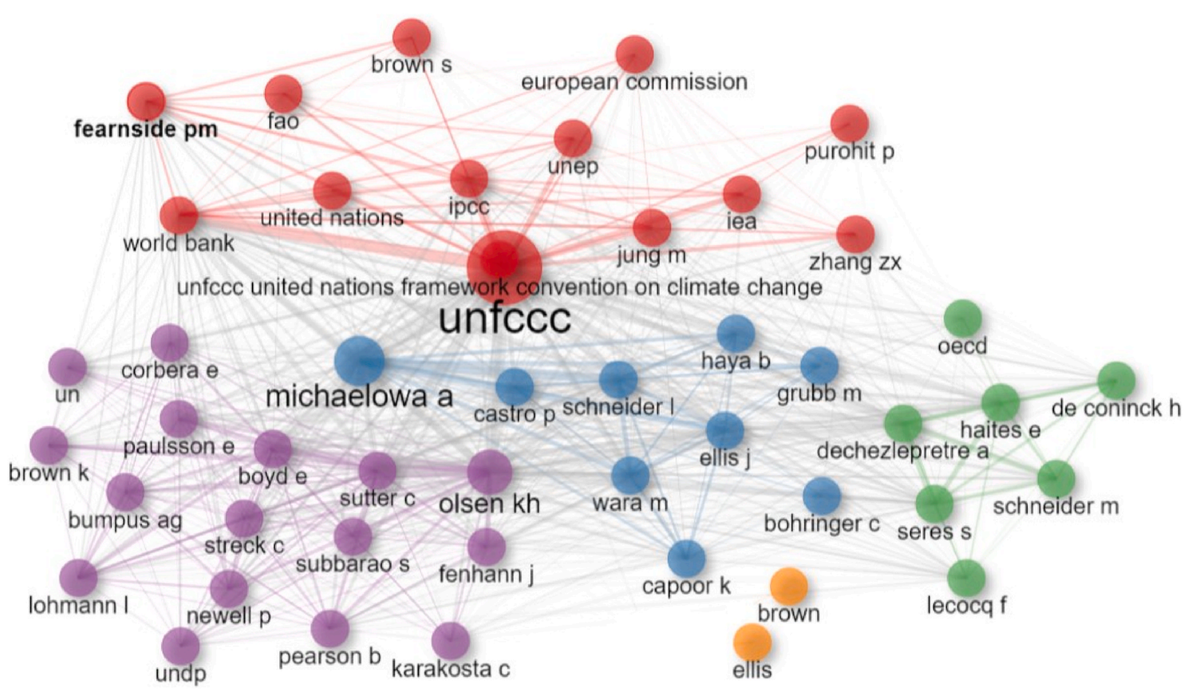

Fig. 5. Collaboration network among the different authors.

Table 3
Ranking of 15 most cited sources.

Ranking	Sources	Citations	Papers	Citations/ Paper	Impact Factor*
1	Energy Policy	3113	105	29.65	6.142
2	Climate Policy	1239	69	17.96	5.085
3	Agriculture Ecosystems and Environment	722	5	144.40	5.567
4	Climatic Change	690	16	43.13	4.743
5	Economic Geography	406	1	406.00	11.767
6	Ecological Economics	396	16	24.75	5.389
7	Journal of Cleaner Production	373	15	24.87	9.297
8	Global Environmental Change-Human and Policy Dimensions	362	8	45.25	9.523
9	Applied Energy	324	11	29.45	9.746
10	Journal of Environment and Development	285	11	25.91	2.097
11	Mitigation and Adaptation Strategies for Global Change	257	29	8.86	3.583
12	Trends in Ecology and Evolution	245	1	245.00	17.712
13	Renewable Energy	236	11	21.45	8.001
14	Environmental Science and Policy	220	9	24.44	5.581
15	International Environmental Agreements-Politics Law and Economics	218	17	12.82	2.649

As can be seen in Table 4, the United States (105) is the most productive, followed by Germany (70), China (66), the United Kingdom (64), and Brazil (35). These five countries account for nearly 42% of all publications. It is worth noting that despite being in fourth place in the number of papers published, the United Kingdom has the highest number of citations (2122), with an average of 33.16 citations per paper.

A notable mention goes to Kenya, which ranks 26th with six publications. However, these six publications have been cited 749 times, giving Kenya the highest average of citations per paper (124.83). Much of the scientific production on CDM came from collaboration among these countries. In this sense, Fig. 7 presents the most relevant collaboration relationships.

Fig. 5 presents the interactions between fifty countries using the Louvain clustering association method (Blondel et al., 2008). The results show the formation of four research groups led by the USA, UK, Germany, and France, which have interacted with each other. Additionally, there was an isolated group consisting of the Philippines and Denmark. Among the main groups, there were notable interactions between USA-China, USA-Germany, USA-Canada, USA-UK, Germany-Switzerland, UK-Netherlands, and France-Brazil. However, the statement does not provide further details on the specific nature of these interactions.

3.3. *Most cited papers (key studies)*

This section is dedicated to analyzing the most cited papers in scientific literature on CDMs, and answering the third research question (RQ3) about what could be considered the key studies. In this sense, Table 5 presents the findings regarding this matter.

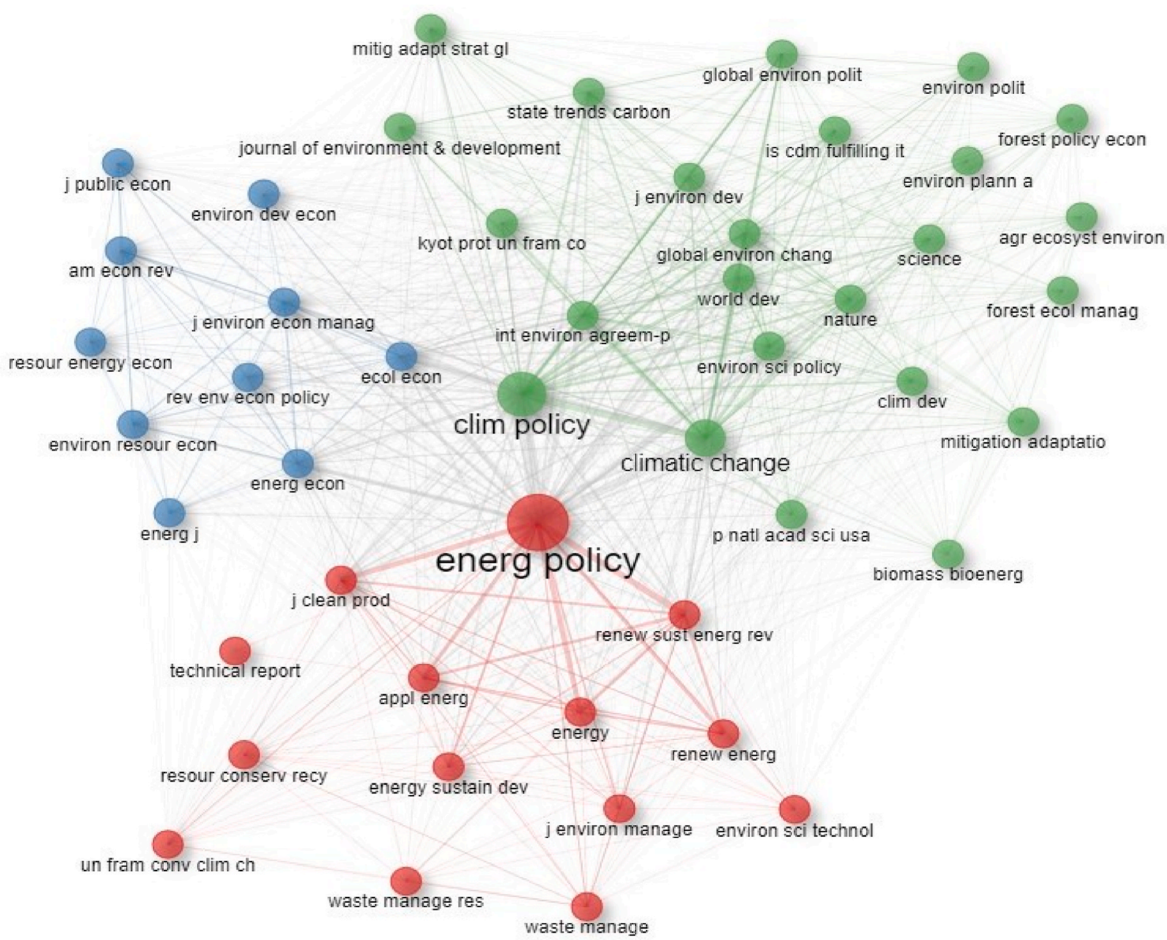

Fig. 6. Collaboration network among the different sources.

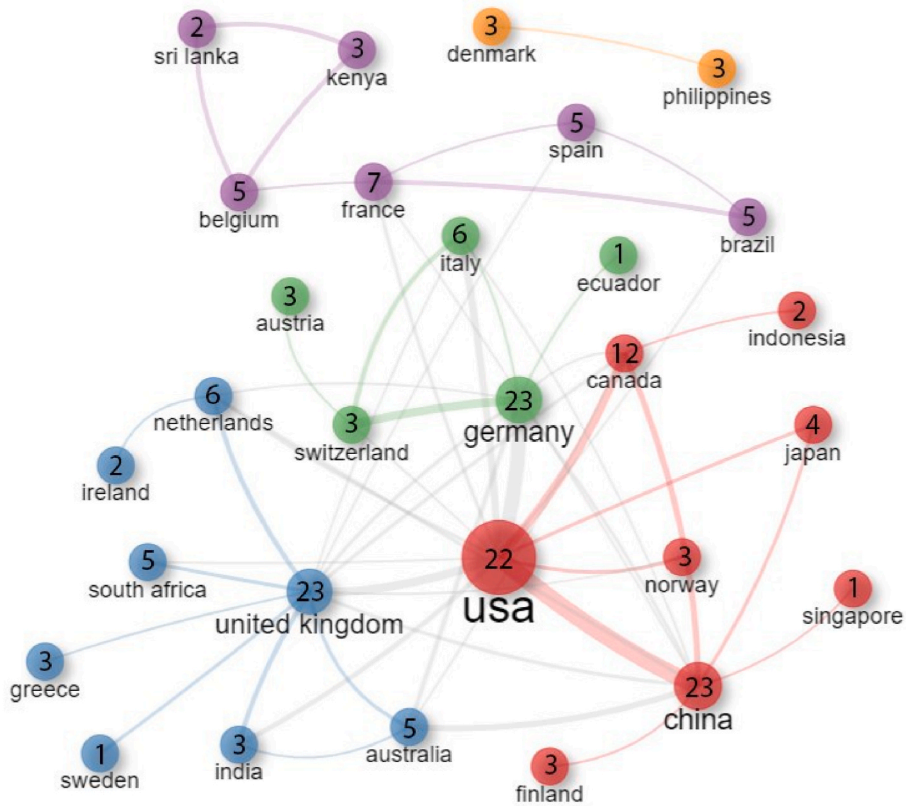

Fig. 7. Collaboration network among the different countries.

Table 4
Scientific production on CDMs per country.

Ranking	Country	Total Papers	Total Citations	Citation/Paper
1	USA	105	1818	17.31
2	Germany	70	1540	22
3	China	66	799	12.11
4	United Kingdom	64	2122	33.16
5	Brazil	35	376	10.74
6	Japan	33	272	8.24
7	India	31	235	7.58
8	Canada	29	760	26.21
9	Netherlands	29	607	20.93
10	Switzerland	25	663	26.52
11	Australia	24	604	25.17
12	France	23	704	30.61
13	Sweden	22	331	15.05
14	Denmark	21	599	28.52
15	Greece	20	305	15.25

Table 5 presents a ranking of CDM-related papers with the highest number of citations and citations per year. In this sense, it is possible to observe that the ranking hardly changes when considering the absolute or annual number, indicating that there is no single paper that stands out from the others when one indicator is considered over the other. However, it is important to note the papers at the top of the table, where it is verified that the paper with the highest number of citations is the one by Zorner R., Trabucco A., and Bossio L., entitled "Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation," with 553 citations (39.50/year), followed by the paper "Accumulation by decarbonization and the governance of carbon offsets" by Bumpus, A., and Liverman, D., with 406 citations (29.00/year) and the paper "Tropical grassy biomes: misunderstood, neglected, and under threat" by Parr, C. L. et al., with 245 citations (30.63/year).

An important aspect to be highlighted is that the topics and approaches of the papers are very diverse (although all related to Clean Development Mechanisms), which may indicate that there are many areas interested in this subject. Another important fact to note is that except for the previously highlighted paper by Parr, C. L. et al., which is from 2014, none of the others in Table 5 are from after 2010, which indicates that for more than a decade, the scientific production on the subject had little impact.

To better understand the relevance of the papers cited in Table 5, a discussion of their main topics is proposed in section 3.3.1. below.

3.3.1. *Discussion of key studies content*

Hepburn (2007) noted that the Industrial Revolution led to the release of almost gigatons of carbon (GtC) into the atmosphere, causing global warming. To limit warming to below 2 °C, the Intergovernmental Panel on Climate Change (IPCC) established that emission levels must remain below 450 parts-per-million (ppm) based on GHG emissions accumulated since the Industrial Revolution.

In 2018, the IPCC warned of the risks involved if warming exceeded 1.5 °C (Masson-Delmotte et al., 2018), and this view was reaffirmed in the agency's latest report (Masson-Delmotte et al., 2021). The issue of land use and deforestation is also significant, with deforestation representing 25% of global emissions (Thomas et al., 2010). Afforestation/reforestation is an important measure to mitigate this problem, but planning and approval of related projects, such as CDM-A/R and REDD+, face difficulties due to the definition of anthropogenically degraded areas versus natural undergrowth (Parr et al., 2014).

However, slowing deforestation and promoting forest regeneration could reduce GHG emissions by 12–15% by 2050 (Klooster and Masera, 2000). Trabucco et al. (2008) found that the hydrological impacts of afforestation/reforestation are significant on local hydrological cycles but have not predicted large impacts on a regional or global scale. Financial constraints are critical to investing in CDM-A/R projects, and

Table 5
Scientific production on CDMs per country.

Ranking	Year	Title	Authors	Source	Citations	Citation/ Year
1	2008	Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation	Zorner, R., Trabucco, A., Bossio, L.	Agriculture Ecosystems and Environment	553	39.50
2	2008	Accumulation by decarbonization and the governance of carbon offsets	Bumpus, A., Liverman D.	Economic Geography	406	29.00
3	2014	Tropical grassy biomes: misunderstood, neglected, and under threat	Parr, C. L. et al.	Trends in Ecology & Evolution	245	30.63
4	2007	The clean development mechanisms contribution to sustainable development: a review of the literature.	Olsen, K.	Climate Change	241	16.07
5	2007	Does the current Clean Development Mechanism (CDM) deliver its sustainable development claim? An analysis of officially registered CDM projects	Sutter, C., Parreño, J. C.	Climate Change	196	13.07
6	2005	Transaction costs, institutional rigidities and the size of the clean development mechanism	Michaelowa, A., Jotzo, F.	Energy Policy	161	9.47
7	2008	The Clean Development Mechanism and the international diffusion of technologies: An empirical study	Dechezleprêtre, A., Glachant, M., Ménière, Y.	Energy Policy	145	10.36
8	2007	Carbon trading: a review of the Kyoto mechanisms	Hepburn, C.	Annual Review of Environment and Resources	131	8.73
9	2009	Reforming the CDM for sustainable development: lessons learned and policy futures	Boyd, E. et al.	Environmental Science & Policy	130	10
10	2000	Community forest management in Mexico: carbon mitigation and biodiversity conservation through rural development.	Klooster, D., Masera, O	Global environmental change	127	5.77
11	2008	Climate change mitigation through afforestation/reforestation: a global analysis of hydrologic impacts with four case studies	Trabucco, A. et al.	Agriculture Ecosystems and Environment	120	8.57
12	2007	CDM: Taking stock and looking forward	Ellis, J. et al.	Energy Policy	113	7.53
13	2010	Why are there so few afforestation and reforestation Clean Development Mechanism projects?	Thomas, S. et al.	Land use policy	112	9.33
14	2008	Sustainable development benefits of clean development mechanism projects: A new methodology for sustainability assessment based on text analysis of the project design documents submitted for validation	Olsen, K. H., Fenhann, J.	Energy Policy	104	7.43
15	2009	Technology transfer by CDM projects: A comparison of Brazil, China, India and Mexico	Dechezleprêtre, A., Glachant, M., Ménière, Y.	Energy Policy	100	7.69

representatives must secure funding to cover project costs from conceptualization and startup until the sale of emission reduction certifications (CERs) (Thomas et al., 2010).

The duality between sustainable development (SD) and CDM projects is also prominent. Sutter and Parreño (2007) found that less than 1% of CERs generated by CDM projects contribute significantly to sustainable development in the host country. Moreover, about 25% of all projects do not have a relevant contribution to sustainable development, nor are they likely to generate real emission reduction. Until 2006, CDM projects did not significantly contribute to SD (Olsen, 2007).

One issue is the need to recognize and respond to the "non-carbon" benefits of CDM projects, as only carbon benefits are valued in the carbon market. Olsen (2007) identified five key issues in how CDMs are failing to achieve SD as guided in the Kyoto Protocol, including defining sustainable development, reducing transaction costs, managing the market, accessing financing and assistance from the international market, and negotiating CDMs after 2012. The difficulty of defining SD and the issue of the sovereignty of countries resulted in the Marrakesh Agreement (UNFCCC, 2001; Peake, 2002), which gave host governments the responsibility to establish criteria for what is, in effect, sustainable development (SD).

The distribution of Clean Development Mechanism (CDM) projects has been heavily concentrated in Asia and Latin America, with only 2.5% of projects established in Africa, according to Boyd et al. (2009). HFC and N2O projects dominate, with half of all HFC projects located in China. Olsen and Fenhann (2008) proposed a taxonomy with 13 criteria for Sustainable Development (SD), where small-scale projects bring a slightly larger number of SD benefits than large-scale projects. Small-scale projects tend to provide more economic and social benefits, except for health benefits, while large-scale projects provide more "other benefits" and environmental benefits, except land and conservation benefits.

Transaction costs are a crucial aspect in the context of CDM projects. Boyd et al. (2009) note that financial investments in small-scale CDM projects are often insufficient to cover transaction costs. Thomas et al. (2010) report that the costs for managing natural forests and afforestation/reforestation projects generally range from US$ 50,000 to US$ 200,000. According to Michaelowa and Jotzo (2005), the average cost of technical assistance and administration can be up to 20.5% of the total CDM project cost for energy efficiency projects and 14.4% for renewable energy projects.

Technology transfer is another important aspect of CDM projects. Transferable projects are typically on a larger scale than non-transferable ones, and having a subsidiary of the company based in the host country clearly favors technology transfer, as noted by Dechezleprêtre et al. (2008) and (2009). Technology transfers through CDM projects are hindered by four types of barriers concerning commercial viability, lack of information, lack of access to capital, and the institutional structure in the host country. The international transfer of technology is strongly correlated with the national technological capacity to absorb these technologies (Dechezleprêtre et al., 2008). China has the highest percentage of projects involving international transfer (59%), while Sub-Saharan Africa hosts only 1.4% of projects. Ellis et al. (2007) note that much of the world's new technologies originate in OECD countries, and private investment flows and Foreign Direct Investment (FDI) have the potential to transfer technologies outside the country of origin. Hepburn (2007) suggests that investments of up to US$ 40 billion per year may be necessary, assuming that developed countries recognize responsibility for greenhouse gas emission reductions of 90% by 2050 and assuming that 50% of their financial effort is directed towards developing countries.

The costs and benefits of climate policies may not be distributed equally among countries. Rich countries' investment in developing countries creates an unequal political economy for commodities. Carbon offsets can be seen as an example of wealth redistribution through "accumulation by dispossession," based on old models of conversion of collective or community property into private property, with colonial control of natural resources by the state through law or military authority (Bumpus and Liverman, 2008). According to Hepburn (2007), the emerging carbon markets represent "neoliberal accumulation by decarbonization," given that the European Union Emissions Trading System (EU-ETS) comprised more than 96% by volume and more than 98% by value of the global carbon markets until that year.

In summary, the most cited papers on CDM projects address various research themes: (i) general sustainability analyses; (ii) land use, including the impacts of deforestation and reforestation; (iii) the duality between SD and greenhouse gas mitigation established by CDM projects; (iv) the impact of transaction costs on the design and implementation of CDM projects; and (v) the perception and absorption of technology transfer between developed and developing countries in CDM projects.

3.4. Main thematic areas

This section aims to answer the fourth research question (RQ4) by analyzing the scientific literature to understand the main thematic axes that involve Clean Development Mechanisms. In this sense, Table 6 presents a list of the main identified clusters and their keywords.

The first cluster presented in Table 6 pertains to CDM projects and their connection with the Kyoto Protocol, containing articles that serve as the foundation for scientific research in this field. The second cluster focuses on studies related to Social Development, and is noteworthy for the strong presence of China and India. While it serves as a core theme, it can also act as a catalyst for other topics. The third cluster encompasses discussions on "CDM projects, Additionality, and Negotiations". Additionality is a crucial requirement for CDM projects, and has gained importance in recent years. CDM projects must demonstrate that their implementation is necessary to achieve the environmental benefits that they provide, and that such benefits would not be achieved in the absence of the project. This concept is closely linked to carbon credits and environmental financing, and is therefore an emerging theme in this field of study.

The fourth cluster pertains to studies that focus on Climate Policy, Carbon Markets, and Offsets. Meanwhile, the fifth cluster deals with an emerging environmental theme, namely afforestation and reforestation projects, along with themes on land use and carbon leakage, with a particular emphasis on Latin America and Mexico.

The sixth cluster focuses on the role of governance and bioenergy, with a strong connection to research and development (R&D) and innovation, which are essential for the success of CDM projects. The seventh cluster is related to climate change, technology transfer, energy efficiency, and sustainable development, and also evaluates economic aspects such as foreign investment and transaction costs.

Another important aspect to expand the analysis is the evolution of terms associated with CDMs in the scientific literature over the years as shown in Fig. 8.

It is possible to observe that in the first years, from 2002 to 2006, the discussion was more related to the greenhouse effect and the Kyoto Protocol. In a second phase, between 2006 and 2008, in addition to terms more associated with environmental aspects, elements related to economy and business, such as "environmental economics, emissions trading, and project management," appeared, indicating a different focus on the phenomenon.

In the period from 2008 to 2010, there was a mix of terms related to the environment, such as "emission controls" and "climate change," with terms related to business and economy, such as "costs" and "transaction costs."

Between 2010 and 2012, in addition to these two lines, terms more related to public policy and development began to emerge, with

Table 6
Clusters of recurrent terms and their associations.

Cluster	Label	Items	Keywords (Occurrences)
1	CDM and Kyoto Protocol	23	Clean Development (29); Mechanism (23); Kyoto (15); Protocol (12); Joint Implementation (10); Baseline (9); Carbon Credits (9); Certified Emission Reductions (7); Activities Implemented Jointly (6); Clean Development Mechanisms (5); Carbon Offset (4); Emission Reductions (4); Risk (4); A/R CDM (3); Carbon Credit (3); Certified Emission (3); CO_2 (3); European Union (3); Global Climate Change (3); Mechanism CDM (3); Performance (3); Reductions (3); Sub-Saharan Africa (3).
2	CDM and Social Development	32	Clean Development (29); Mechanism (23); Kyoto (15); Protocol (12); Joint Implementation (10); Baseline (9); Carbon Credits (9); Certified Emission Reductions (7); Activities Implemented Jointly (6); Clean Development Mechanisms (5); Carbon Offset (4); Emission Reductions (4); Risk (4); A/R CDM (3); Carbon Credit (3); Certified Emission (3); CO_2 (3); European Union (3); Global Climate Change (3); Mechanism CDM (3); Performance (3); Reductions (3); Sub-Saharan Africa (3).
3	CDM Additionality and Negotiations	21	Clean Development (29); Mechanism (23); Kyoto (15); Protocol (12); Joint Implementation (10); Baseline (9); Carbon Credits (9); Certified Emission Reductions (7); Activities Implemented Jointly (6); Clean Development Mechanisms (5); Carbon Offset (4); Emission Reductions (4); Risk (4); A/R CDM (3); Carbon Credit (3); Certified Emission (3); CO_2 (3); European Union (3); Global Climate Change (3); Mechanism CDM (3); Performance (3); Reductions (3); Sub-Saharan Africa (3).
4	CDM, Climate Policy and Carbon Markets	17	Climate Policy (30); Carbon Markets (17); Governance (12); Carbon Offsets (10); Climate (10); Greenhouse Gas (8); Paris Agreement (6); Emission (5); Political Economy (5); Change (4); Climate Governance (3); Finance (3); Global (3); Methodologies (3); Offset Markets (3); Rural Electrification (3); Stakeholder (3).
5	CDM and Projects of Forestry	19	Carbon (16); Afforestation (14); Reforestation (14); Forestry (11); Land Use (10); Institutions (6); Cameroon (4); Forests (5); Leakage (5); Co-Bene ts (4); Deforestation (4); Land-Use Change (4); Latin America (4); Mexico (4); CDM-Ar (3); Community Forestry (3); Forest (3); Methodology (3); Plantations (3).
6	CDM and Governance	38	CDM (146); Africa (14); Sustainability (13); Carbon Trading (11); UNFCCC (10); Climate Finance (8); Land ll (8); Redd (7); Innovation (6); Thailand (6); Capacity Building (5); Cers (5);

(continued on next page)

Table 6 (*continued*)

Cluster	Label	Items	Keywords (Occurrences)
			Composting (5); Least Developed Countries (5); Policy (5); Waste Management (5); Biomass (4); Environmental Governance (4); Municipal Solid Waste (4); Technology (4); Transfer (4); Uganda (4); Waste-To-Energy (4); Bagasse Cogeneration (3); Bangladesh (3); Bioenergy (3); Carbon Finance (3); Climate Change Policy (3); Combined Heat and Power (3); Electricity Generation (3); Environmental Bene ts (3); Indonesia (3); Model (3); Options (3); R & D (3); Sustainable Energy (3); Vietnam (3); Waste (3).
7	CDM, Technology Transfer and Sustainable Development	38	Clean Development Mechanism (291); Kyoto Protocol (102); Climate Change (89); Sustainable Development (72); Technology Transfer (45); Renewable Energy (37); Developing Countries (25); Carbon Sequestration (23); Emissions Trading (22); Carbon Market (18); Brazil (13); Energy E ciency (13); Global Warming (12); Greenhouse Gases (11); South Africa (9); Transaction Costs (9); Wind Power (7); CO_2 Emissions (6); Pollution (5); Agriculture (4); Barriers (4); Biofuels (4); Decision Support (4); Flexible Mechanisms (4); Foreign Direct Investment (4); Markets (4); Agroforestry (3); Benefits (3); Case Study (3); Cluster Analysis (3); Developing (3); Efficiency (3); International Climate Policy (3); Property Rights (3); Social (3); Technological Capabilities (3); Technology Diffusion (3); Trade (3).

emphasis on “sustainable development” and “energy policy.” In the period from 2012 to 2014, the previous lines continued, receiving new terms associated with innovation and technology transfer, such as “technology-transfer-benefits,” “diffusion,” and “innovation.” All these lines seem to continue until today with a recent focus on India and China, probably because they are two of the countries where most CDM projects have been carried out.

4. Conclusion and policy implications

This study aimed to analyze the relevant scientific research on Clean Development Mechanisms. To achieve this objective, four research questions were proposed to guide the construction of a bibliometric study on the subject.

Based on the results obtained, the initial conclusion is that the scientific production on this topic grew from 2006 to 2013, but decreased afterwards, following the trend of the growth and decline of CDM project registrations. This relationship deserves attention from the academic community as CDMs continue to play a crucial role in sustainability and sustainable development, presenting several noteworthy phenomena that warrant further investigation.

The results also allow us to draw an important conclusion about identifying prominent contributors to scientific production on the topic. The USA has the highest volume of published studies, followed by Germany and China. Energy Policy and Climate Policy are the most prominent scientific journals that publish on the subject. Notable authors include Antônio Trabucco, Diana M. Liverman, Robert J. Zomer, Deborah A. Bossio, and Adam G. Bumpus. These findings provide insights into the dynamics of scientific production on the theme and its main references, which can guide scientific cooperation and future studies.

A third important conclusion that can be drawn from the results is the identification of key studies in the scientific literature on the subject, including “Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation”, published in the journal Agriculture, Ecosystems & Environment in 2008; “Accumulation by Decarbonization and the Governance of Carbon Offsets”, published in the journal Economic Geography in 2008; and “Tropical grassy biomes: misunderstood, neglected, and under

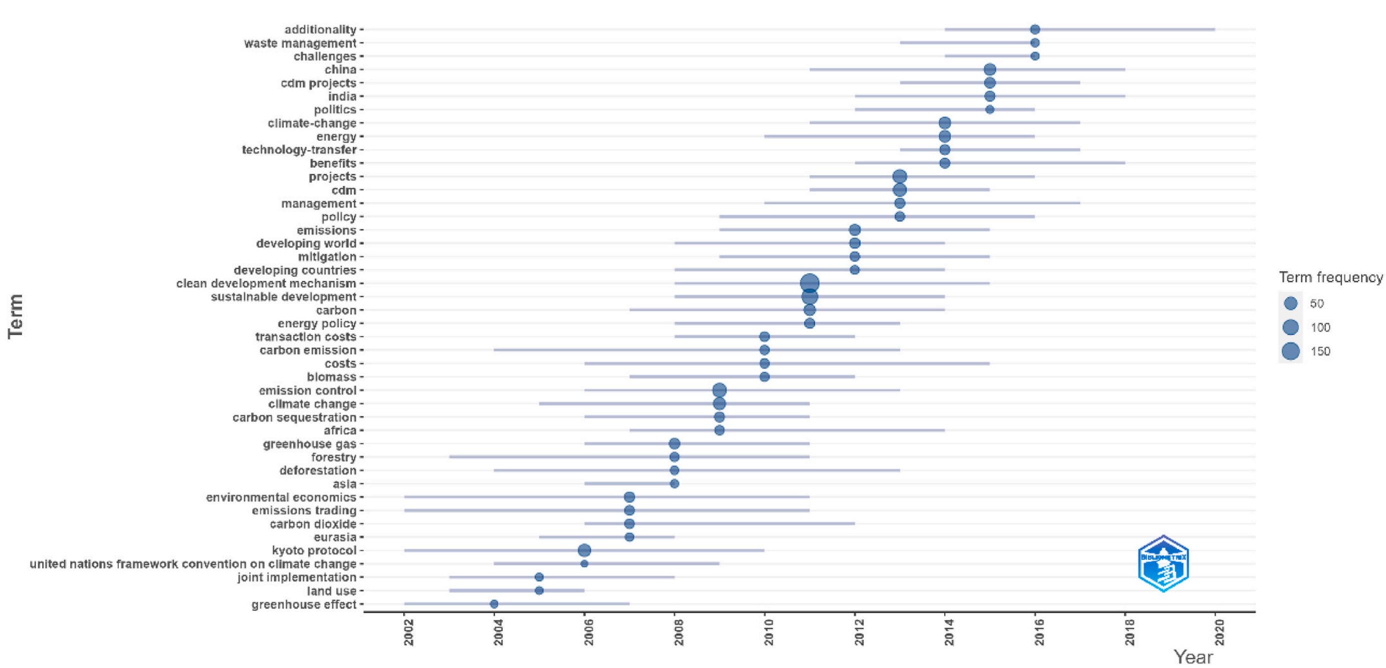

Fig. 8. Evolution of CDM terms through the years.

threat", published in the journal Trends in Ecology & Evolution in 2014. These studies are considered seminal due to their high number of citations, and their relevance is widely recognized by other researchers.

Finally, the last conclusion that the results show is related to the main thematic axes present in the scientific literature on CDMs. Through the analysis of keywords, four main axes of research were identified and expanded into seven thematic groups, covering the main subjects studied by researchers in the field. This finding is particularly relevant as it guides researchers in positioning new studies within the identified axes and seeking clearer references, in addition to identifying gaps in topics that have not yet been adequately explored in the scientific literature.

Regarding the implications of energy policy, the findings indicate that academic interest in the topic decreased from 2012 onwards, accurately reflecting the lack of interest in implementing Clean Development Mechanism (CDM) projects after this date. These projects have been an important element in greenhouse gas mitigation, which is why host country governments need to create incentives to attract more projects, whether they are economic, infrastructural, or of another type. It is important to highlight that a significant portion of these projects also generate energy (many of them renewable), either for local consumption or for resale, thereby contributing to expanding the energy mix of host countries (developing and non-developed countries) and making it cleaner.

Another relevant aspect is that the largest thematic cluster found in this study is that of energy policy, demonstrating the importance of studying this subject in the academic world. This, in turn, reflects how significant this topic is for society and indicates to public policymakers the importance of considering CDM projects in the development of strategies related to clean energy generation and distribution in their countries.

It is also important to discuss the limitations of this research. Although it was a broad investigation of the scientific production on CDMs, it was not exhaustive. Only two databases (Scopus and Web of Science) were considered, and only articles from scientific journals in the English language and with Digital Object Identifier (DOI) were included. Books, articles from scientific conferences, and theses and dissertations were not included, which means that there may be relevant findings in sources that were not explored in this study.

Lastly, the authors offer three suggestions for future research based on their experience with this study. The first suggestion is to investigate the reasons for the decline in scientific production on the subject after 2013, which can provide a more comprehensive understanding of the research dynamics. The second suggestion involves further exploration of each of the thematic axes identified in this study to identify gaps and opportunities for new research. The third and final suggestion is related to the lack of papers in most journals that include quantitative analyses of the actual contributions of the CDMs to GHG abatement. This is crucial for evaluating the real impact of these projects and should receive more attention from both journals and researchers.

CRediT authorship contribution statement

Wagner Wilson Bortoletto: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Antonio Carlos Pacagnella Junior:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Otavio Gomes Cabello:** Conceptualization, Validation, Investigation, Resources, Writing – review & editing, Visualization, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT (https://chat.openai.com/) in order to revise the English writing. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests

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Data availability

Data will be made available on request.

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