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Implications of Machine Learning in the Generation of Renewable Energies in Latin America from a Globalized Vision: A Systematic Review

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ABSTRACT

The global energy industry fundamentally transformed towards renewable energy sources, driven by the sustainability paradigm. This shift was crucial in addressing the challenges of climate change and resource scarcity. Machine Learning (ML) played a pivotal role in enhancing the efficiency and reliability of renewable energy systems. This study conducted a comprehensive analysis of scientific production at the intersection of ML and renewable energy generation, focusing on Latin America. Employing a methodology based on documentary research and bibliometric processes, utilizing the Scopus database with the support of R and VOS viewer software, our research revealed a significant increase in interest and investment in research related to ML and renewable energies since 2020. This exponential growth scenario in this knowledge area had significant implications for Latin America and the world, fostering technological advancements and the adoption of renewable energies. Countries such as China, India, the United States, South Korea, and Saudi Arabia represented 61% of the global scientific production in this field, underscoring its global relevance. This growth indicated a growing interest and investment in ML applications in renewable energies, aligning with the 2030 Agenda for Sustainable Development. This research aligns with the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation, and Infrastructure). It contributed to progress toward a more sustainable future, benefiting society through more efficient and sustainable energy systems, the energy industry through increased innovation and the adoption of clean technologies, and Latin America, which could leverage these findings to sustainably drive its economic and environmental development.

Keywords: Machine Learning, Power Generation, Renewable Energies
JEL Classifications: A30, Q42, Q56

1. INTRODUCTION

Sustainability is a paramount concern for contemporary society, industries, and governments (Chambers et al., 2021). The current production and transformation systems, heavily reliant on non-renewable resources, teeter on the brink of an irreversible depletion of these vital natural sources that underpin humanity and ecosystems (Mahari et al., 2021). In response to this pressing global challenge, nations introduced the Millennium Goals in the previous century, serving as a beacon for a unified global agenda promoting species preservation, ecosystem health, human dignity, and more. However, grappling with the complexities of operationalizing sustainability, driven by vast disparities among nations and profound technological and cultural shifts induced by globalization, the Sustainable Development Goals (SDGs) emerged in 2015 as a central component of the 2030 agenda (Castro et al., 2022). This comprehensive agenda lays a blueprint for a genuinely sustainable global future, featuring 17 objectives and over 160 goals addressing issues like clean energy, infrastructure development, and climate action, among others (Boar et al., 2020). Within this revitalized sustainability context, the energy industry is recognized as one of the world's foremost sources of pollution and consumers of non-renewable resources, exemplified by SDG 7, "Affordable and clean energy." This goal outlines strategies and targets for accessible, clean energy generation and transmission for humanity (Li et al., 2023; Manotas et al., 2021).

In contrast to the past, the energy industry has begun committing to generating alternative energies, which consume fewer resources and exert less impact on ecosystems, in acknowledgment of its profound influence on Earth's sustainability (Laimon et al., 2022). Senior leaders in the energy industry view sustainability as a strategic norm that drives organizational transformation, balancing efficiency, efficacy, environmental impact, and widespread access to energy services (Schwanitz and Wierling, 2022). This equilibrium acknowledges that new technologies, often called moderators or catalysts by experts, play a pivotal role in reshaping the energy industry toward genuine sustainability (Martinez-Sierra et al., 2019; Ghobakhloo and Fathi, 2021). Within this framework, Industry 4.0 technologies like the Internet of Things, blockchain, artificial intelligence, and ML play a pivotal role (Ghobakhloo and Fathi, 2021; Samper et al., 2022).

In the case of machine learning, it has maintained a close relationship with the energy industry since its inception, as evidenced by studies such as "Machine Learning and Deep Learning in Energy Systems: A Review" and "A Review on the Integrated Optimization Techniques and machine learning approaches for modeling, prediction, and decision making on integrated energy systems." These studies highlight the profound impact of ML on enhancing renewable energy generation and transformation processes in recent years (Alabi et al., 2022; Forootan et al., 2022).

Considering the critical role of technological surveillance in the sustainable energy industry, particularly in machine learning, this study endeavors to characterize the scientific production related to ML in renewable energy generation, focusing on Latin America. This emphasis is well-justified by the imperative to bridge the gap in adopting and applying cutting-edge technologies in the Latin American context, where countries like Peru and Colombia have historically lagged in sustainability compared to their more developed counterparts (Palma et al., 2020; Garcia-Samper et al., 2022).

2. METHODOLOGY

This study is based on bibliometric processes, an area of scientific observation aimed at research in the form of scientific products such as scientific articles, book chapters, and other written typologies (Ramírez-Duran et al., 2023). A systematic literature search was conducted in the Scopus database in June 2023 with the keywords "Machine learning," "Renewable energies," and "Power generation" below. Table 1 shows the standardization of the keywords.

The search equation posed in Scopus was: (TITLE-ABS-KEY ("Machine learning") AND TITLE-ABS-KEY ("Renewable energies") OR TITLE-ABS-KEY ("alternative energies") OR TITLE-ABS-KEY ("clean energies") OR TITLE-ABS-KEY ("green energies") AND TITLE-ABS-KEY ("Power generation") OR TITLE-ABS-KEY ("Energy generation"); 745 results related to the research topic were obtained and cover a period between 1999 and 2023.

Table 1: Keyword standardization

Keywords	Descriptors
Machine learning	*Machine learning
Renewable energies	*Alternative energies
	*Clean energies
	*Green energies
Power generation	*Energy generation

Table 2: Main information of the data obtained from Scopus

Main information about data	
Timespan	2014:2023
Sources (Journals, Books, etc.)	157
Documents	410
Annual Growth Rate %	65.07
Document average age	1.76
Average citations per doc	16,05
References	20010
Document Contents	
Keywords plus (ID)	2873
Author's keywords (DE)	1284
Authors	
Authors	1515
Authors of single-authored docs	17
Authors Collaboration	
Single-authored docs	18
Co-Authors per Doc	4.19
International co-authorships %	34.15
Document Types	
article	410

Table 3: Lotka's law

Written documents	N. of Authors	Proportion of authors
1	1383	0.913
2	98	0.065
3	28	0.018
4	2	0.001
5	2	0.001
6	1	0.0007
7	1	0.0007

Table 4: Bradford's law

Zone	No. Journals	No. Titles	Percentages
Zone 1	7	140	34.15
Zone 2	33	136	33.17
Zone 3	117	134	32.66

Figure 1: Research methodology

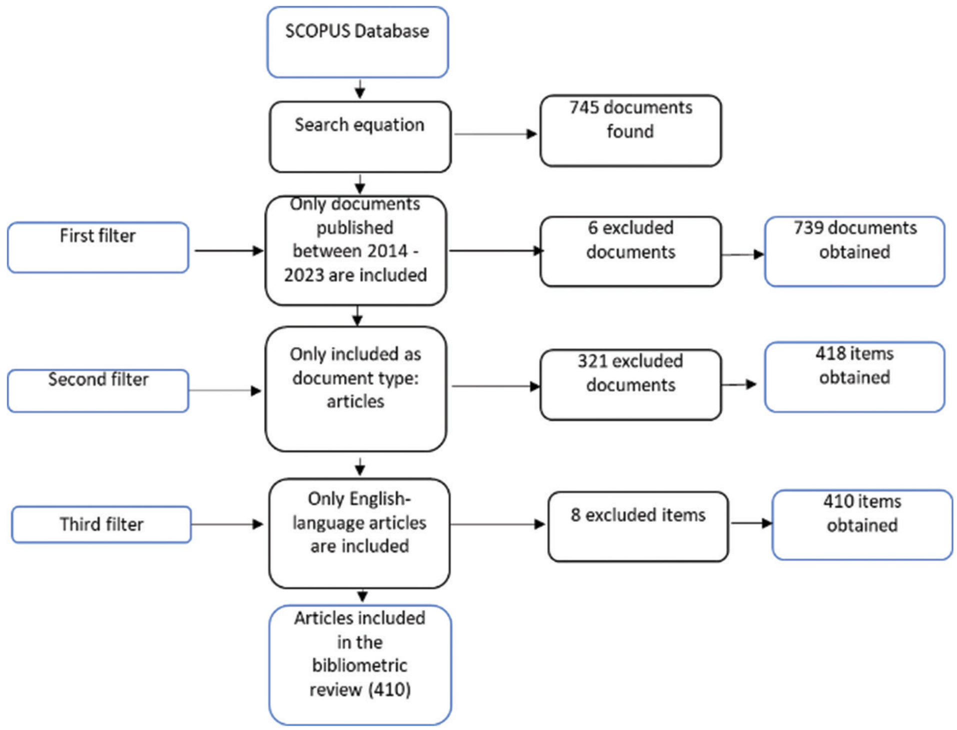


Figure 2: Lotka's Law, source: author based on information from Scopus (2023)

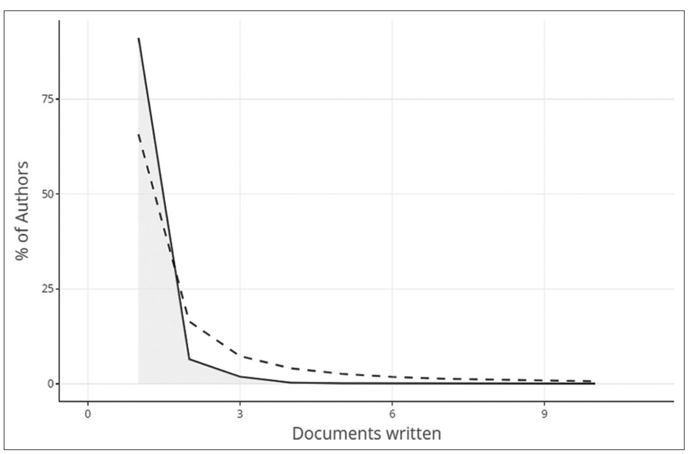


Figure 3: Bradford's Law, source: author based on information from Scopus (2023)

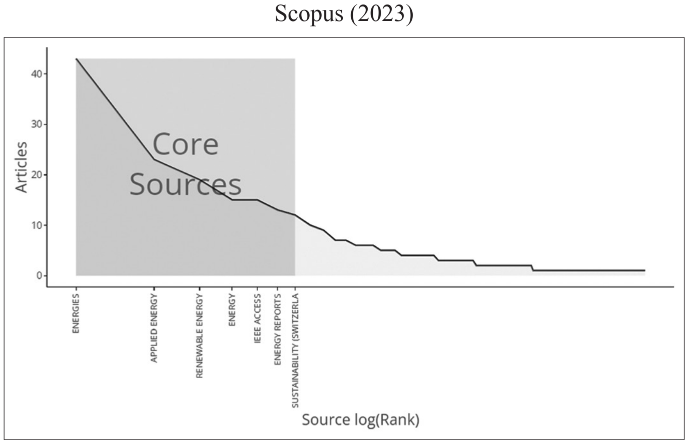


Figure 4: Annual scientific production, source: author based on information from Scopus (2023)

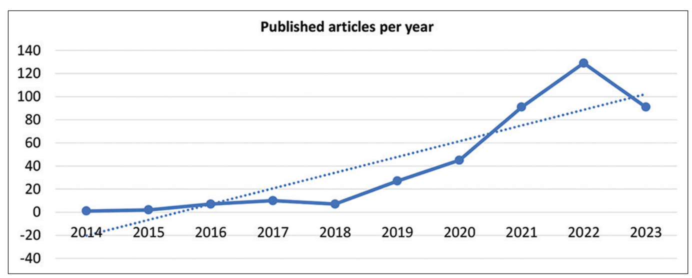
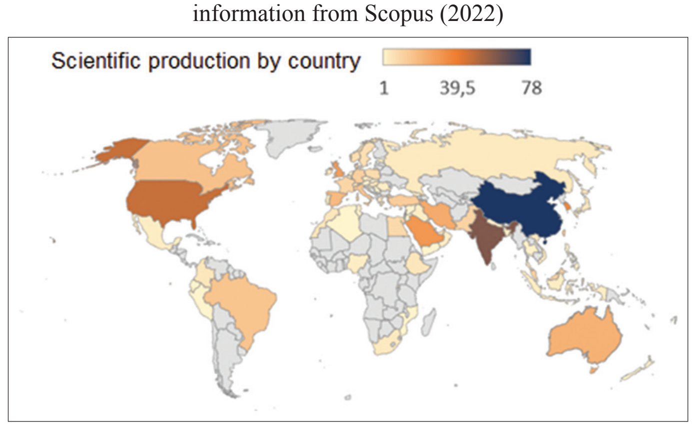


Figure 5: Scientific production by country, source: author based on information from Scopus (2022)



To these results obtained from the search equation, 3 filters were applied, as shown in Figure 1. The first filter only includes documents published from 2014 to 2023; 739 were obtained, and 6 were excluded. The second filter is that the published documents are articles; 418 were obtained, and 321 were excluded. The third filter is

Table 5: Latin American countries

Country	Article	Authors	Journal
Brazil	Development of a hybrid computational intelligent model for daily global solar radiation prediction.	Goliatt and Yaseen (2023).	Expert Systems with Applications
	Approaches for the short-term prediction of natural daily streamflows using hybrid machine learning enhanced with grey wolf optimization.	Martinho et al. (2023).	Hydrological Sciences Journal
	Assessing the impact of hydropower projects in Brazil through data envelopment analysis and machine learning.	Bortoluzzi et al. (2022).	Renewable Energy
	Ridge regression ensemble of machine learning models applied to solar and wind forecasting in Brazil and Spain.	Carneiro et al. (2022).	Applied Energy
	Solar Irradiance Forecasting to Short-Term PV Power: Accuracy Comparison of ANN and LSTM Models.	Wentz et al. (2022).	Energies
	Prediction-free, real-time flexible control of tidal lagoons through Proximal Policy Optimisation: A case study for the Swansea Lagoon.	Moreira et al. (2022).	Ocean Engineering
	Efficient bootstrap stacking ensemble learning model applied to wind power generation forecasting.	Ribeiro et al. (2022).	International Journal of Electrical Power and Energy Systems
	A Comparison Between Deep Learning and Support Vector Regression Techniques Applied to Solar Forecast in Spain.	Lima et al. (2022).	Journal of Solar Energy Engineering, Transactions of the ASME
	Electrical load demand forecasting using feed-forward neural networks.	Machado et al. (2021).	Energies
	Solar irradiance prediction with machine learning algorithms: A Brazilian case study on photovoltaic electricity generation.	de Freitas Viscondi and Alves-Souza (2021).	Energies
	A low-cost iot system for real-time monitoring of climatic variables and photovoltaic generation for smart grid application.	de Melo et al. (2021).	Sensors
	Ultrasound-based identification of damage in wind turbine blades using novelty detection.	Oliveira et al. (2020).	Ultrasonics
	Extended isolation forests for fault detection in small hydroelectric plants.	de Santis and Costa (2020).	Sustainability (Switzerland)
	Multiple site intraday solar irradiance forecasting by machine learning algorithms: MGGP and MLP neural networks.	Mendonça de Paiva et al. (2020).	Energies
	Energy production predication via Internet of Thing based machine learning system.	Rebouças Filho et al. (2019).	Future Generation Computer Systems
	Design Principles and Top Non-Fullerene Acceptor Candidates for Organic Photovoltaics.	Lopez et al. (2017).	Joule
Colombia	Machine learning applications for photovoltaic system optimization in zero green energy buildings.	Liu et al. (2020).	Energy Reports
	Predictive Modeling of Photovoltaic Solar Power Generation.	Gil-Vera and Quintero-López (2023).	WSEAS Transactions on Power Systems
	Machine Learning for Solar Resource Assessment Using Satellite Images.	Ordoñez Palacios et al. (2022).	Energies
	Cloud and machine learning experiments applied to the energy management in a microgrid cluster.	Rosero et al. (2021).	Applied Energy
	A comparison of the performance of supervised learning algorithms for solar power prediction.	Gutiérrez et al. (2021).	Energies
Mexico	Power Disturbance Monitoring through Techniques for Novelty Detection on Wind Power and Photovoltaic Generation.	Gonzalez-Abreu et al. (2023).	Sensors
	A smart simulation-optimization framework for solar-powered desalination systems.	Aldaghi et al. (2022).	Groundwater for Sustainable Development
	A Machine-Learning Pipeline for Large-Scale Power-Quality Forecasting in the Mexican Distribution Grid.	Flores et al. (2022).	Applied Sciences (Switzerland)
Ecuador	Smart monitoring method for photovoltaic systems and failure control based on power smoothing techniques.	Arévalo et al. (2023).	Renewable Energy
Peru	Machine learning applications for photovoltaic system optimization in zero green energy buildings.	Liu et al. (2023).	Energy Reports

that the articles are in English; 8 were excluded, and 410 articles were obtained. Finally, with these, the bibliometric review is carried out.

The results obtained were exported from Scopus in CSV format; the Excel program, the Bibliometrix package of the R software, and the VOSviewer software were used for the information analysis. From this, various indicators were generated that allow analyzing the number of articles published, the authors with the largest number of publications, the dynamics of the sources, institutions, and countries with more publications in the area; the general information of the published articles is presented in Table 2.

Table 2 shows the main information of the articles of the final consultation in a time interval from 2014 to 2023. The bibliometric review was carried out with 410 articles that meet the established criteria.

Table 6: Most cited articles

Articles	DOI	Total of Citations
Persson et al. (2017)	10.1016/j.solener. 2017.04.066	224
Golestaneh et al. (2016)	10.1109/TPWRS.2015.2502423	205
Bódis et al. (2019)	10.1016/j.rser. 2019.109309	169
Assouline et al. (2017)	10.1016/j.solener. 2016.11.045	143
Zhang et al. (2016)	10.1016/j.enconman. 2016.01.023	136
Sharifzadeh et al. (2019)	10.1016/j.rser. 2019.03.040	135
Ahmad et al. (2018)	10.1016/j.energy. 2018.08.207	133
Lopez et al. (2017)	10.1016/j.joule. 2017.10.006	132
Huang et al. (2019)	10.1109/ACCESS.2019.2921238	128
Ak et al. (2016)	10.1109/TNNLS.2015.2418739	118
Li et al. (2016)	10.1016/j.renene. 2015.12.069	101
Assouline et al. (2018)	10.1016/j.apenergy. 2018.02.118	90
Liu et al. (2020)	10.1016/j.jclepro. 2019.119272	87
Elmaz et al. (2020).	10.1016/j.energy. 2019.116541	87
Shi et al. (2020)	10.1016/j.apenergy. 2020.115733	86
Aslam et al. (2019)	10.3390/en13010147	78
Aznarte and Siebert (2017)	10.1109/TPWRD.2016.2543818	78
Xia et al. (2021)	10.1109/TII.2021.3056867	72
Wang et al. (2019)	10.1109/JIOT.2018.2877510	69
Shrivastava et al. (2016)	10.1016/j.renene. 2015.08.038	69

3. RESULTS AND DISCUSSION

The study began with an analysis of bibliometric productivity, followed by an examination of various bibliometric indicators, and concluded with an investigation of relationships and co-occurrences.

3.1. Laws of Bibliometric Productivity

It is observed that a small number of authors contribute significantly to scientific production, while a larger group of authors contributes fewer articles. This pattern reflects a quantitative relationship between authors and their contributions in a specific field over time (Alves, 2019; Barrera Suárez et al., 2021).

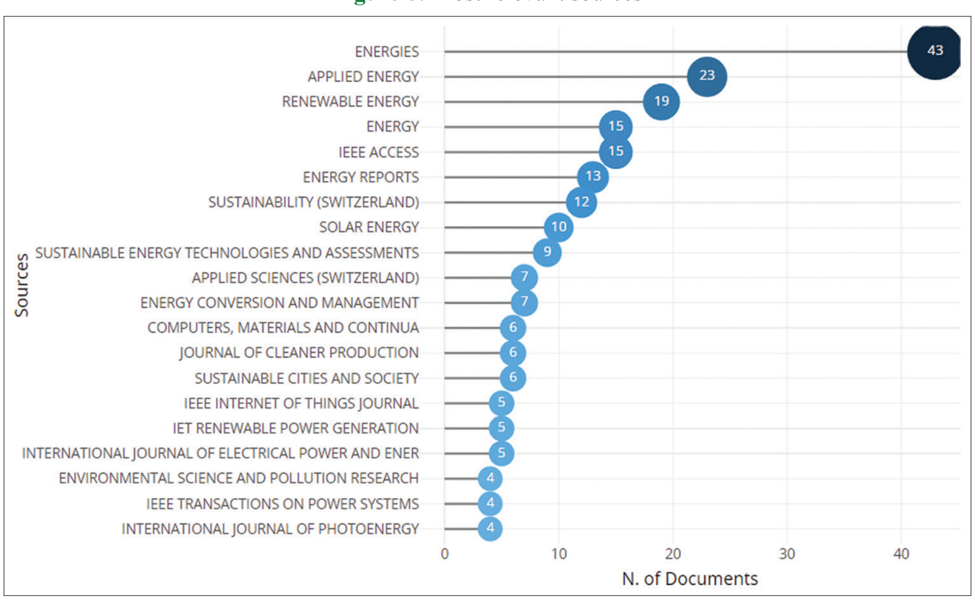
Figure 2 and Table 3 provide evidence of compliance with Lotka's Law. Many authors (1383), accounting for 91% of the total, have contributed only one article each. In contrast, the remaining 9%, equivalent to 132 authors, have made at least two contributions. Notably, seven is the maximum number of articles published by a single author. This data suggests that most publications in this field result from researchers conducting relatively transient research on the topic under study.

These observations underscore the importance of understanding the dynamics of scientific productivity, as they have significant implications for how researchers and scholars approach research in each field.

On the other hand, when applying Bradford's Law, as demonstrated in Table 4, it is observed that 34.15% of the published articles are concentrated in the first 7 journals, which, in turn, belong to zone 1 of Bradford's Law. This zone describes the behavior of journal distribution based on productivity, where zone 1 houses a relatively small number of journals but the most productive ones (Gregorio-Chaviano et al., 2020).

Among these journals, the top 4 deserve special mention, as illustrated in Figure 3, accounting for 71% of the total publications

Figure 6: Most relevant sources



among journals within Zone 1 of Bradford: Energies, Applied Energy, Renewable Energy, and Energy.

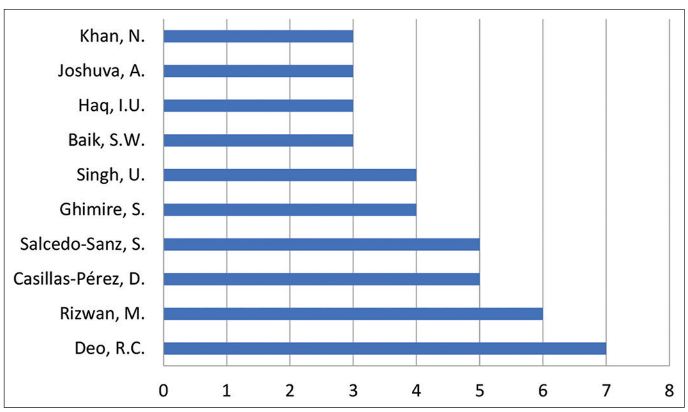
This underscores the significance of these journals as significant research sources in the field, as they concentrate a substantial proportion of publications and can, therefore, provide valuable insights and essential information for researchers and professionals in the field.

3.2. Bibliometric Indicators

Figure 4 highlights the years 2020 (45), 2021(91), 2022(129), and 2023(91), in which there was a notable growth in publications related to the research topic, and 87% of all research carried out is concentrated. On the other hand, at a general level, between 2014 and 2023, the graph shows a growing trend in scientific production related to the subject.

A geographical analysis was carried out to know the countries in which they have published the most regarding the research topic. Figure 5 shows the map of the countries that make contributions to the field of study. We can highlight China (78), India (60), the United States (47), South Korea (35), and Saudi Arabia (31). These countries contribute 61% of all publications in the field of study.

Figure 7: Most relevant authors



The study has a Latin American focus, so Table 5 shows the countries published on the subject.

According to Table 5, Brazil (n = 16) is the Latin American country that has published the most articles related to ML in generating renewable energies, followed by Colombia (n = 5). Concerning Brazil, one of their articles addresses the prediction of wind energy production through ML based on the Internet of Things (Rebouças Filho et al., 2019). In turn, these propose the design of a low-cost system based on the Internet of Things for monitoring climate variables that affect the generation of photovoltaic energy (Melo et al., 2021).

On the other hand, two of the published articles address solar radiation prediction through ML algorithms for photovoltaic energy generation (Mendonça de Paiva et al., 2020; de Freitas Viscondi and Alves-Souza, 2021). Similarly, Colombia has research on predicting photovoltaic energy from ML algorithms fed with historical data and satellite images (Ordoñez Palacios et al., 2022; Gil-Vera and Quintero-López, 2023). Another article addresses the use of ML techniques to model the production of photovoltaic energy for a system in Medellín (Gutiérrez et al., 2021).

On the other hand, an analysis of the most relevant sources in the research topic was carried out; Figure 6 shows that the 4 journals that publish the most on the subject are Energies (43), Applied Energy (23), Renewable Energy (19) y Energy (15).

The journal "Energies" has several of its publications that refer to research on wind energy production prediction using ML (Singh et al., 2021; Bochenek et al., 2021; Alkesaiberi et al., 2022). Production per author is low compared to the number of articles published from 2014 to 2023. As can be seen in Figure 7, the author with the most published articles is Deo R.C., with seven publications.

Several of Deo R.C.'s articles are focused on predicting solar radiation through climate models, observational predictors, and hybrid algorithms between Deep learning and machine learning (Yeom et al., 2020; Ghimire et al., 2022a; Ghimire et al., 2022b).

Figure 8: Co-authoring relationship

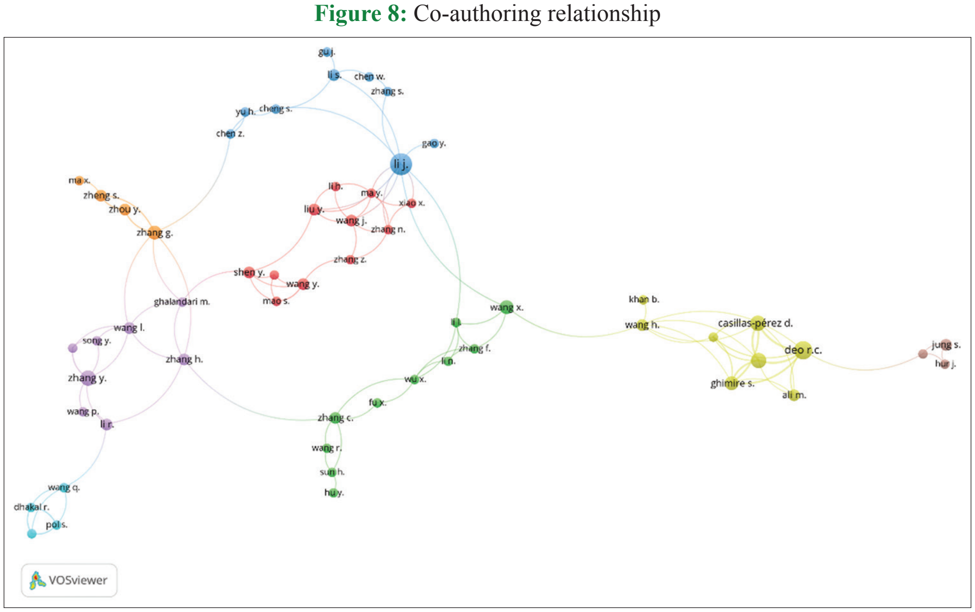


Figure 9: Co-occurrence of keywords using VOSviewer software based on information from Scopus

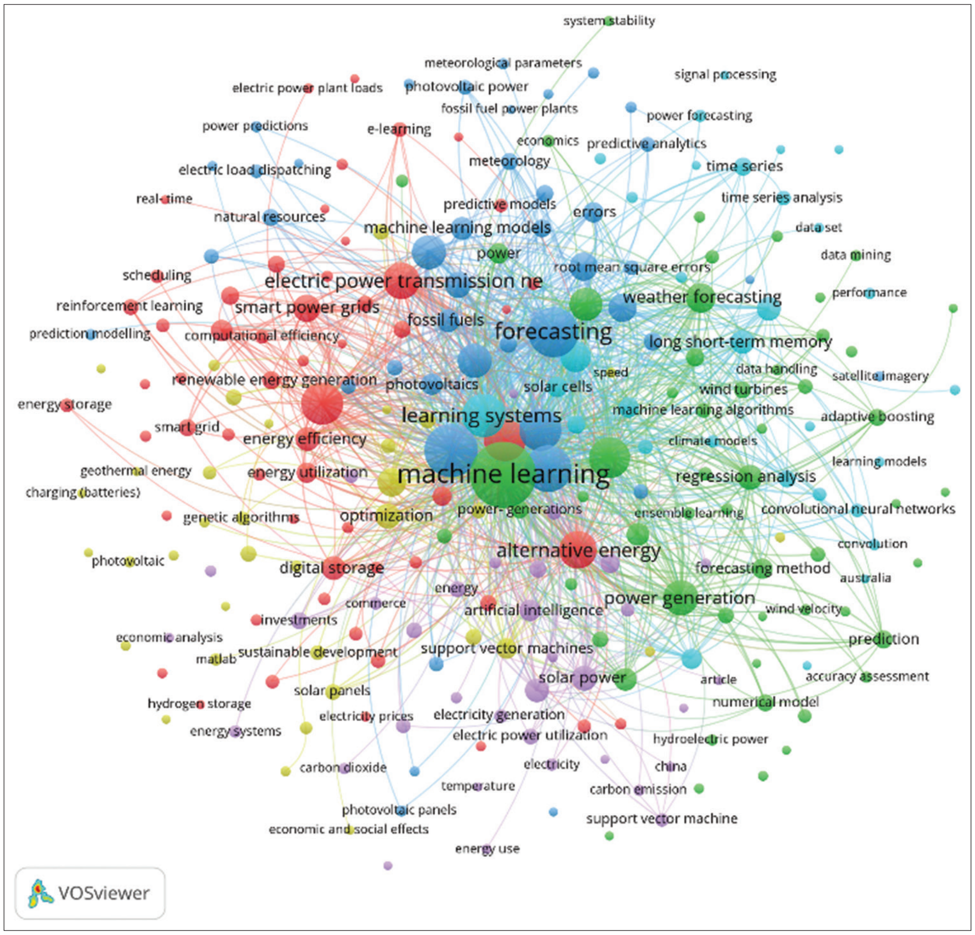


Figure 10: Keywords using R software based on information from Scopus

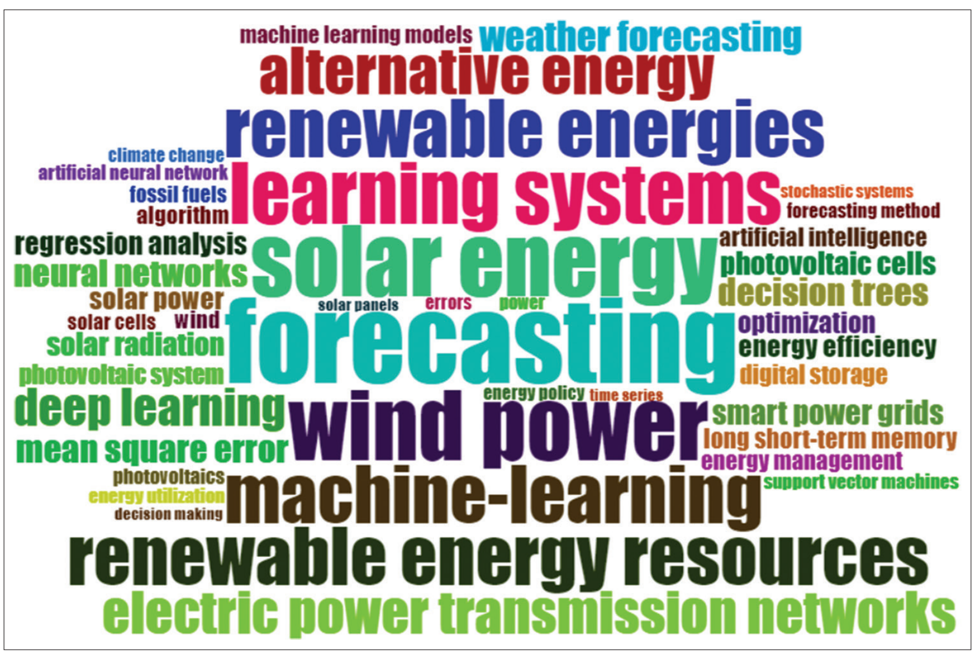


Table 6 shows the 20 publications that have the most citations; the three most representative are Persson et al. (2017), Golestaneh et al. (2016), and Bódis et al. (2019).

The analysis of relationships and co-occurrences is done using the VOSviewer software, taking as a parameter that the author has at least two documents and two citations.

The co-authorship analysis shows that of 1515 authors, 132 meet the parameters, and of these, only 57 have works with other authors, which shows that more collaborative work is needed between authors interested in the subject of study. This scenario can be seen in Figure 8, in which eight clusters can be identified.

Finally, a co-occurrence analysis of keywords was performed. The parameter was that the minimum number of occurrences of a keyword is 5 of 2873 words; only 255 meet the parameter. This trend can be evidenced in Figures 9 and 10, where 6 clusters are identified; the words can be highlighted: machine learning, solar power generation, forecasting, learning systems, renewable energies and alternative energy.

4. CONCLUSIONS

The comprehensive bibliometric analysis of 410 articles, extracted from Scopus, focusing on ML in renewable energy generation, provided valuable insights and underscored the relevance of this research area.

Firstly, the analysis from 2014 to 2023 revealed an escalating trend in scientific production related to this topic, signifying a growing interest. Notably, the years from 2020 to 2023 witnessed a substantial surge, with 87% of total articles concentrated within this period.

Secondly, the geographical distribution of publications highlighted the global significance of this research. China, India, the United States, South Korea, and Saudi Arabia emerged as major contributors, collectively accounting for 61% of all publications. In contrast, Latin American nations, including Brazil, Colombia, Ecuador, and Peru, contributed, representing 6% of the total publications within this domain.

Furthermore, our analysis pinpointed influential journals as primary platforms for disseminating research. Journals such as Energies, Applied Energy, Renewable Energy, and Energy stood out, concentrating 24% of the publications. The remaining articles were distributed across various journals.

Lastly, our study illuminated the role of researchers in this field. Deo R.C. emerged as the leading author, with seven publications, shedding light on the substantial contributions of a few key researchers. Notably, our analysis indicated that 91% of researchers engaged in this area tended to be transient, emphasizing the dynamic nature of this field.

This bibliometric study underscored the increasing importance of ML in renewable energy research. It revealed global interest, with specific countries and journals playing pivotal roles. Moreover, it highlighted the prominent role of a select group of researchers. This analysis provided critical insights for academics and professionals and underscored the relevance and dynamism of this research area in addressing pressing energy and sustainability challenges.

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