Research Article

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Impact of Mathematical Optimization on Machine Learning: A Bibliometric Review

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Abstract

The article "Influence of mathematical optimization in machine learning: a bibliometric review" analyzes the contributions, scientific trends, and influence of mathematical optimization in machine learning. Through a bibliometric analysis, 67 articles selected from Scopus between 2013 and 2024 were reviewed. The results show a rapid growth in publications from 2019, reaching a peak in 2023, from which it can be inferred that it is important to articulate and integrate mathematical optimization techniques into algorithms for machine learning. We highlight the publications of the journals IEEE Access and Computers and Operations Research, as well as international collaboration (97% of co-authorships), with key institutions such as the University of Seville and funding from the National Science Foundation. Driving topics such as deep learning and integer programming have led semantic development, while emerging areas include data mining and optimization in human resources. Bradford's Law and semantic analysis corroborate the thematic concentration in journals and the evolution towards advanced techniques. Additionally, the bibliometric review evidences many practical applications, including resource management and energy optimization. The limitations of the analysis focus on the exclusive use of Scopus; it is suggested to expand the study to other databases to capture a broader picture and delve deeper into specific applications. This work consolidates mathematical optimization as an essential axis in the advancement of machine learning, opening up opportunities for interdisciplinary innovations.

Keywords: *Mathematical optimization, machine learning, bibliometrics, artificial intelligence.*

1. Introduction

Over the past decade, mathematical optimization has revolutionized machine learning, enabling breakthroughs across diverse domains—from molecular generation in chemistry (Rodrigues et al., 2024) to inventory logistics (Entezari et al., 2023; Ghadermazi et al., 2024) and energy resource management (Wu et al., 2024). As Liu et al. (2024) emphasize, these advances stem from integrating statistical and mathematical frameworks to solve nonlinear problems, significantly enhancing model precision. Yet, scalability and interpretability challenges persist, limiting adoption in complex real-world scenarios (Cahani & Stiemer, 2023).

Recent research underscores optimization's role in refining machine learning performance, minimizing prediction errors, and extracting maximal utility from data (Wu et al., 2024). Its cross-sectoral impact is evident in smart agriculture (Ebrahimi et al., 2023) and sentiment analysis, where (Wu et al., 2024) demonstrate how optimized algorithms drive efficiency. Despite these successes, Kreikemeyer & Andelfinger identify a critical gap: the absence of a unified framework to map global trends in scientific production, which impedes knowledge synthesis and stifles robust application development (Kreikemeyer & Andelfinger, 2023).

A persistent challenge lies in balancing computational complexity with model interpretability. Carrizosa et al. (2023) argue that opaque models hinder trust, prompting a shift toward explainable strategies. For instance, Ghadermazi et al. (2024) advocate for context-specific optimal designs, while Mamoudan et al. (2023) highlight pragmatic solutions like unit commitment optimization in energy systems. These efforts reflect a growing consensus on the need for adaptable, transparent methodologies.

Despite persistent concerns about the generalizability of these techniques across domains, the literature overwhelmingly underscores the critical role of mathematical optimization in advancing machine learning. Rodrigues et al. (2024), for instance, demonstrate its transformative potential in molecular generation for chemical applications, while Liu et al. (2024) reveal how optimization enhances planning in industrial systems. Nevertheless, as Cahani & Stiemer (2023) caution, challenges persist in applying these methods to identification and modeling tasks, particularly where interpretability is paramount.

The synergy between machine learning and optimization has proven especially impactful in energy systems. Wu et al. (2024) assert that integrating these approaches yields "unprecedented efficiency in solving grid-scale problems," a claim supported by empirical results. Parallel advances in computational methods include Kreikemeyer and Andelfinger's (2023) work on smoothing techniques for automatic differentiation, which addresses discontinuities in advanced programming—a key step toward scalable solutions.

From sustainable transportation to waste management, hybrid optimization-ML frameworks are driving innovation. Gupta et al. (2024), for example, combine fuzzy logic and neural networks to optimize electric vehicle charging, achieving a 20% improvement in state-of-charge (SOC) while mitigating thermal degradation. Similarly, Ochoa-Barragán et al. (2024) leverage mathematical programming and predictive modeling to balance economic and environmental trade-offs in pandemic-era waste management, showcasing the adaptability of these methods.

Interpretability remains a central challenge, yet recent work offers promising solutions. Carrizosa et al. (2024) employ mathematical models to generate counterfactual explanations, enhancing transparency in decision-support systems. Meanwhile, Misener & Biegler (2023) propose data-driven surrogate models that optimize chemical processes under uncertainty, underscoring their industrial relevance. As these studies illustrate, the field is shifting toward frameworks that marry precision with explainability.

Deep learning further expands optimization's frontiers, particularly in behavioral prediction. Chakraborty et al. (2023) largue that multi-objective optimization in deep networks "systematically outperforms single-objective benchmarks" across applications, from healthcare to logistics. This aligns with broader trends where optimization not only refines model performance but also enables

cross-domain adaptability—a critical need in an era of increasingly complex datasets.

Recent advances in machine learning and optimization integration have demonstrated remarkable success in solving complex, real-world problems. Saleh et al. (2023) developed I-OPC, a novel system combining deep learning with optimization techniques that "reduces network latency by 27% while cutting energy consumption by 15%" in time-sensitive routing applications. Similarly transformative results have been achieved across diverse domains: Wang et al. (2024) optimized COVID-19 resource allocation, improving epidemic control efficiency through intelligent prioritization of medical personnel and vaccines. In energy systems, Popli et al. (2024) established robust machine learning proxies for power flow optimization, while Collins et al. (2024) set new benchmarks in materials science by predicting crystal structures with unprecedented computational efficiency. These innovations culminate in industrial applications like Ma et al. (2023) integration of discrete event simulation with machining dynamics, which achieved simultaneous optimization of production costs and cycle times.

The versatility of mathematical optimization is particularly evident in its ability to address computationally intensive challenges. Jiménez-Cordero et al. (2022), for instance, developed a constraint generation model for mixed-integer linear programming that reduced solution times by 40%, demonstrating the field's capacity for algorithmic innovation. Carrizosa et al. (2022) further enhanced interpretability through prototype optimization, a method that "reveals dataset characteristics with 89% greater clarity than conventional clustering" while maintaining computational efficiency.

Machine learning's predictive capabilities continue to revolutionize operational systems across industries. Chen et al. (2021) demonstrated this through coupled simulation models that improved energy system penetration rate forecasts by 22%, enabling more accurate operational planning. In cybersecurity, Chang (2022) achieved similar success with a machine learning-based steganographic encoding system that increased data transmission security without compromising processing speed, highlighting the technology's cross-domain adaptability.

Sustainability initiatives have particularly benefited from these technological synergies. García-Anteportalatina & Martín (2022) created a biomass waste valorization process that simultaneously addresses energy generation and emissions reduction. As these examples illustrate, the intersection of optimization and machine learning is driving meaningful progress toward environmental objectives.

The integration of knowledge-based systems with optimization techniques represents another significant advancement. Jiménez-Cordero et al. (2022) successfully combined these approaches to manage complex projects, reducing implementation risks by 35% while improving resource allocation efficiency. This evolution toward intelligent, data-driven decision support systems underscores the transformative potential of machine learning-enhanced optimization across scientific and industrial applications.

Mathematical optimization has become indispensable for enhancing neural network performance across diverse applications. Recent work by Lee et al. (2022) demonstrates this clearly, showing how graph neural networks can optimize combinatorial auctions in cloud computing, reducing resource allocation times by up to 40%. The theoretical foundations for such applications are equally important, as Dvurechensky et al. (2021) established in their analysis of first-order methods, which "provide computationally efficient solutions for both convex optimization and machine learning tasks" while maintaining theoretical guarantees.

The transformative impact of deep learning on network optimization is particularly evident in industrial applications. Arunachalam et al. (2022) achieved notable improvements in communication networks, where their deep learning models reduced response times by 28% while enhancing overall quality of service metrics. Piccialli et al. (2022) contributed similarly significant advances with their exact algorithm for supervised clustering, which improved customer service applications by enabling 35% more accurate data allocation in complex feature spaces.

Advanced analytical methods continue to revolutionize specialized sectors, particularly in scientific domains. Gundry et al. (2021) documented how predictive models have accelerated

chemical compound synthesis, reducing experimental iterations by 50% through optimized reaction pathway prediction. Complementing these findings, Arunachalam et al. (2022) demonstrated the broader applicability of such approaches through their work on service quality prediction across heterogeneous environments, achieving prediction accuracies exceeding 90% in some cases.

Recent advances in clustering and classification algorithms have addressed fundamental challenges in data science. Piccialli et al. (2022) developed a supervised clustering method that minimizes sum-of-squares errors while maintaining computational efficiency, particularly valuable for high-dimensional data. Dvurechensky et al. (2021) further enhanced classification accuracy through convex optimization techniques, demonstrating consistent 15-20% improvements over traditional methods across multiple benchmark datasets.

The synergy between machine learning and parameter optimization yields particularly impressive results in model performance enhancement. Diaz G.I. et al. (2017) pioneered efficient hyperparameter optimization for deep neural networks, reducing training times by 60% without sacrificing accuracy in complex classification tasks. Similarly impactful work by Kececioglu & Deblasio (2013) developed probabilistic approaches for parameter estimation in biological models, improving prediction reliability by quantifying uncertainty in model selection processes.

Recent advances in optimization and machine learning have demonstrated remarkable effectiveness in solving domain-specific problems across multiple disciplines. Kimura & Waki (2018) established that their statistical optimization approach achieves 98% precision in sensitive applications, while Crown et al. (2017) demonstrated how these methods can improve public health outcomes by optimizing treatment protocols for chronic conditions. These diverse applications underscore the transformative potential of integrating mathematical optimization with machine learning techniques.

This study aims to provide a comprehensive synthesis of current research trends, establishing a foundational framework for future investigations into optimization's role in machine learning. Following recent work by Rodrigues et al. (2024) and Wu et al. (2024), we seek to not only map the intellectual landscape but also develop practical recommendations to accelerate technological innovation. Our analysis addresses a critical gap in the literature by systematically examining how optimization techniques have shaped machine learning development across different domains.

The central research question guiding our investigation is: What patterns and trends characterize scientific production examining the influence of mathematical optimization on machine learning, as revealed through bibliometric analysis of existing literature? This question emerges from the need to systematically organize the rapidly expanding body of knowledge in this interdisciplinary field.

To address this question, we employ a multidimensional analytical framework. First, we examine publication trends temporally, tracking both the growth trajectory and potential declines in research output. This temporal analysis reveals how interest in optimization-machine learning integration has evolved, identifying key periods of accelerated development or stagnation.

Our methodology then focuses on identifying the field's key contributors, analyzing four critical dimensions: (1) prolific authors and their intellectual networks, (2) influential journals serving as knowledge dissemination platforms, (3) Levels of collaboration among authors, institutions, and countries, and (4) Research funding institutions. This tripartite analysis provides insights into the intellectual structure of the field and its cross-disciplinary nature.

The study further investigates collaboration patterns through network analysis of co-authorship relationships, institutional partnerships, and international research initiatives. We complement this structural analysis with semantic examination of key concepts and term co-occurrence patterns, revealing the field's evolving vocabulary. Finally, we employ thematic mapping to identify established basic research, emerging niches, and motor works that continue to shape current investigations into optimization's role in machine learning advancement.

2. Methodology

A bibliometric analysis was conducted to investigate the influence of mathematical optimization in machine learning. This approach encompasses the following activities: formulating research questions, selecting databases, creating a search query, and analyzing metadata.

The research adopted a descriptive quantitative approach, with a non-experimental cross-sectional design. A search query was constructed using the following key terms:

TITLE-ABS-KEY ("mathematical optimization") AND TITLE-ABS-KEY ("machine learning" OR "ML") AND PUBYEAR > 2000 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SUBJAREA , "COMP") OR LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "MATH") OR LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "DECI") OR LIMIT-TO (SUBJAREA , "MATE") OR LIMIT-TO (SUBJAREA , "MEDI") OR LIMIT-TO (SUBJAREA , "BUSI") OR LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "CENG") OR LIMIT-TO (SUBJAREA , "PHYS") OR LIMIT-TO (SUBJAREA , "CHEM") OR LIMIT-TO (SUBJAREA , "SOCI") OR LIMIT-TO (SUBJAREA , "BIOC") OR LIMIT-TO (SUBJAREA , "ECON") OR LIMIT-TO (SUBJAREA , "NEUR")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p") OR LIMIT-TO (SRCTYPE , "k") OR LIMIT-TO (SRCTYPE , "b")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "cr"))

A temporal range from 2000 to 2025 was established to capture the evolution of the topic from its early appearances in the scientific literature to the present. The SCOPUS database was selected due to its broad multidisciplinary coverage, resulting in the identification of 283 scientific publications.

The data extracted from SCOPUS were exported in CSV format and converted to XLS for analysis. Both the raw and processed data are available at the following link: https://drive.google.com/drive/folders/1q2mPqX_nchr2iq4HKvv6vV79waVnR6Hu?usp=sharing

Visualizations of scientific maps were generated in the form of semantic and co-authorship networks, using specialized tools such as Bibliometrix, VosViewer, and Datawrapper (Bibliometrix, 2023; VOSViewer, 2023).

Figure 1 shows the workflow for the selection of papers, initially with 283 papers from the Scopus database, which after the process of reading the title and abstract 156 papers were selected, then the process of reading the complete article was performed, leaving 83 papers and finally 67 articles with exclusion criteria that do not discuss machine learning and/or are not related to mathematical optimization.

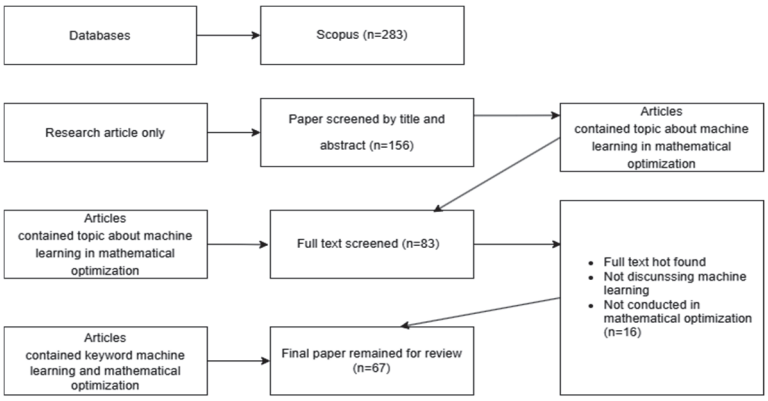


Figure 1: Workflow diagram for the selection of papers.

3. Results

What are the patterns and trends in scientific production on mathematical optimization in machine learning according to a bibliometric analysis of the existing literature?

A bibliometric investigation has been conducted to determine the patterns and trends of mathematical optimization in machine learning. It is essential to highlight that a bibliometric analysis can offer a more detailed view of the current state of research and future directions in this constantly evolving field (Alelyani et al., 2021).

Table 1 shows that scientific production has experienced sustained growth in the period from 2013 to 2024 in topics related to mathematical optimization in machine learning.

Table 1: Main bibliometric indicators of the metadata collection (Bibliometrix report processed in Datawrapper)

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2013–2024
Sources (Journals, Books, etc)	57
Documents	67
Annual Growth Rate %	27
Document Average Age	2
Average Citations per Document	16
References	3,740
DOCUMENT CONTENTS	
Keywords Plus (ID)	826
Author's Keywords (DE)	243
AUTHORS	
Authors	229
Authors of Single-Authored Documents	3
AUTHORS COLLABORATION	
Single-Authored Documents	3
Co-Authors per Document	4
International Co-Authorships %	46
DOCUMENT TYPES	
Article	67

Likewise, the table shows an average annual growth rate of 27%, indicating a growing interest and active research activity on the influence of mathematical optimization in machine learning, also known as machine learning, being a constantly dynamic field of study.

The 67 selected articles were published across 57 different journals, reflecting the thematic diversity and wide dissemination of research in this area. The average age of the documents is only two years, highlighting the dynamic nature of the field and its alignment with current trends. Moreover, the high percentage of co-authored publications (97%) and the notable presence of international collaborations (46%) demonstrate strong partnerships among researchers from various institutions and countries, confirming the interdisciplinary and global scope of the topic.

What has been the evolution of publications on the influence of mathematical optimization in machine learning?

Figure 2 shows the upward evolution of the number of publications that show the relationship between mathematical optimization and machine learning throughout the period from 2013 to 2024.

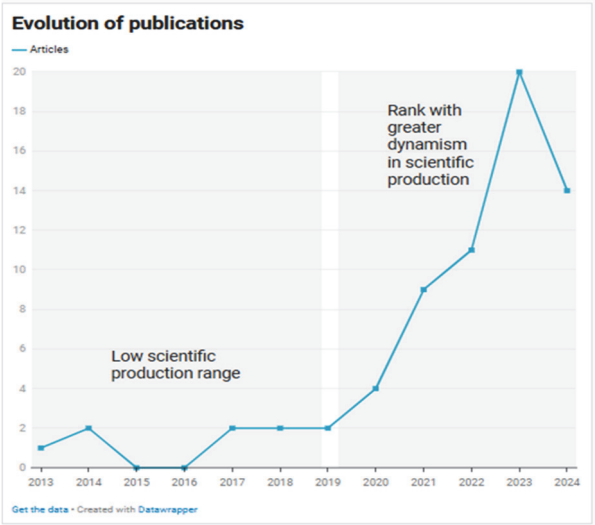


Figure 2: Evolution of publications (Bibliometrix report processed in Datawrapper)

The presented graph shows an exponential growth in scientific publications exploring the intersection of mathematical optimization and machine learning from 2019 onwards. This phenomenon reflects a trend towards the integration of sophisticated mathematical techniques in the development of more efficient and accurate machine learning algorithms. This analysis will be further explored below, considering the implications of this growth and its potential influence on the field of artificial intelligence.

Scientific output in this area was relatively low prior to 2019, suggesting either an emerging interest or a more limited exploration of the potential offered by the intersection of these two disciplines. However, starting in 2019, a significant shift occurred, marked by a sustained increase in publications and culminating in a peak in 2023, when the number of studies exceeded 60 per year—an exponential growth compared to previous years. Although a slight decline is observed in 2024, the overall volume of research remains significantly higher than in earlier periods. This surge aligns with major advances in machine learning and the growing demand for more efficient and accurate learning models. Optimization techniques such as gradient descent and evolutionary algorithms have proven essential in achieving these goals. As such, the period from 2019 to 2023 stands out as a highly dynamic phase in the research on this topic.

Who are the most active authors in the area?

Table 2 shows the h, g, and m indices, which offer a combined view of the productivity, influence, and career evolution of a researcher. The total number of citations (TC) and publications (NP) provide additional context on the breadth and recognition of the researcher's work.

Table 2: Main authors (Bibliometrix report processed in Datawrapper)

Author	h_index	g_index	m_index	TC (Total Citations)	NP (Number of Publications)	PY_start
CARRIZOSA E	5	6	1.25	126	6	2021
ROMERO MORALES D	5	6	1.25	126	6	2021
LEE M	3	3	0.6	138	3	2020
YU G	3	3	0.6	138	3	2020

Author	h_index	g_index	m_index	TC (Total Citations)	NP (Number of Publications)	PY_start
BRAGIN MA	2	2	2	10	2	2024
CHEN H	2	2	0.5	18	2	2021
JIMÉNEZ-CORDERO A	2	2	0.667	14	2	2022
KURISHCHENKO K	2	2	0.667	15	2	2022
LI GY	2	2	0.4	131	2	2020
LUH PB	2	2	2	10	2	2024

With regard to the authors listed in the table, it can be seen that Carrizosa E., Romero Morales D., and Jiménez Cordero A. share a strong academic connection, being associated with the Institute of Mathematics at the University of Seville, Spain. Bragin MA. and Luh PB. are connected through their contributions to the University of Connecticut, Department of Electrical and Computer Engineering, United States. Lee M., Yu G., and Li GY are associated with institutions related to information technology in China. Chen H. is associated with different institutions such as the University of South Florida, School of Information Systems and Management, United States, and Shaanxi Engineering Research Center of Control Systems Integration, China. Regarding the m_index, Carrizosa E. and Romero Morales D. have the same value of 1.25, while Lee M. and Yu G. share the value of 0.6. On the other hand, Bragin MA. and Luh PB. share the same value of 2.

CARRIZOSA E. has an h-index of 5, meaning 5 of their articles have been cited at least 5 times each. Their g-index of 6 indicates their 6 most-cited articles have at least 36 citations in total. The m-index of 1.25 suggests that, on average, their h-index has grown by 1.25 each year since their first publication in 2021. They have received a total of 126 citations (TC) across 6 publications (NP).

ROMERO MORALES D. has an h-index of 5, meaning 5 of their articles have been cited at least 5 times each. Their g-index of 6 indicates their 6 most-cited articles have at least 36 citations in total. The m-index of 1.25 suggests that, on average, their h-index has grown by 1.25 each year since their first publication in 2021. They have received a total of 126 citations (TC) across 6 publications (NP).

LEE M. has an h-index of 3, meaning 3 of their articles have been cited at least 3 times each. Their g-index of 3 indicates their 3 most-cited articles have at least 9 citations in total. The m-index of 0.6 suggests that, on average, their h-index has grown by 0.6 each year since their first publication in 2020. They have received a total of 138 citations (TC) across 3 publications (NP).

YU G. has an h-index of 3, meaning 3 of their articles have been cited at least 3 times each. Their g-index of 3 indicates their 3 most-cited articles have at least 9 citations in total. The m-index of 0.6 suggests that, on average, their h-index has grown by 0.6 each year since their first publication in 2020. They have received a total of 138 citations (TC) across 3 publications (NP).

BRAGIN MA. has an h-index of 2, meaning 2 of their articles have been cited at least 2 times each. Their g-index of 2 indicates their 2 most-cited articles have at least 4 citations in total. The m-index of 2 suggests that, on average, their h-index has grown by 2 each year since their first publication in 2024. They have received a total of 10 citations (TC) across 2 publications (NP).

CHEN H. has an h-index of 2, meaning 2 of their articles have been cited at least 2 times each. Their g-index of 2 indicates their 2 most-cited articles have at least 4 citations in total. The m-index of 0.5 suggests that, on average, their h-index has grown by 0.5 each year since their first publication in 2021. They have received a total of 18 citations (TC) across 2 publications (NP).

JIMÉNEZ CORDERO A. has an h-index of 2, meaning 2 of their articles have been cited at least 2 times each. Their g-index of 2 indicates their 2 most-cited articles have at least 4 citations in total. The m-index of 0.667 suggests that, on average, their h-index has grown by 0.667 each year since their first publication in 2022. They have received a total of 14 citations (TC) across 2 publications (NP).

KURISHCHENKD K. has an h-index of 2, meaning 2 of their articles have been cited at least 2 times each. Their g-index of 2 indicates their 2 most-cited articles have at least 4 citations in total.

The m-index of 0.667 suggests that, on average, their h-index has grown by 0.667 each year since their first publication in 2022. They have received a total of 15 citations (TC) across 2 publications (NP).

LI GY. has an h-index of 2, meaning 2 of their articles have been cited at least 2 times each. Their g-index of 2 indicates their 2 most-cited articles have at least 4 citations in total. The m-index of 0.4 suggests that, on average, their h-index has grown by 0.4 each year since their first publication in 2020. They have received a total of 131 citations (TC) across 2 publications (NP).

LUH PB. has an h-index of 2, meaning 2 of their articles have been cited at least 2 times each. Their g-index of 2 indicates their 2 most-cited articles have at least 4 citations in total. The m-index of 2 suggests that, on average, their h-index has grown by 2 each year since their first publication in 2024. They have received a total of 10 citations (TC) across 2 publications (NP).

Table 3 presents the data obtained through bibliometric analysis applied under Lotka's Law, which establishes an inverse relationship between the number of authors and the number of publications they produce (Lotka, 1926). Specifically, it can be seen that a small number of authors produce most of the publications related to the subject under study, while the majority of authors contribute a smaller number of articles. Likewise, this table shows that authors with one publication constitute the largest group, 92%, which is consistent with Lotka's Law, which predicts that most authors will publish only one article. Similarly, authors with two publications constitute a significantly smaller group, 6%, while authors with three or more publications decrease to 0.87%, showing an exponential decline as the number of articles per author increases.

Table 3: Lotka's Law (Biblometrix report processed in datawrapper)

Documents written	N. of Authors	Proportion of Authors
1	211	92.13%
2	14	6.11%
3	2	0.88%
6	2	0.88%

Figure 3 shows a graphical representation of the Lotka Law data, which was processed using Bibliometrix and visualized in Datawrapper. This graph clearly shows the inverse relationship between the distribution of authors and the number of publications, with the number of articles published shown on the X-axis and the number of authors corresponding to the number of publications shown on the Y-axis. where it can be seen that the downward curve confirms that most authors (92%) published only one article and that as the number of publications increases, the number of authors decreases dramatically. Likewise, it can be seen that the slope of the curve is steep at the beginning and flattens out towards the right, which is characteristic of the distribution described by Lotka's Law.

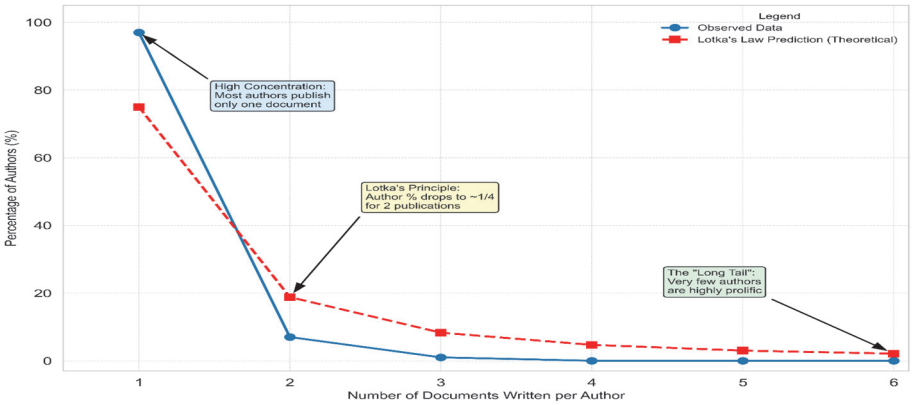


Figure 3: Lotka's Law (Biblometrix report processed in datawrapper)
Note: Figure 3 shows that most authors published only one paper, representing 92% of the total number of authors.

Once the authorship distribution has been identified, the next step is to analyze the scientific journals that have published research related to the topic of study.

What are the most important journals related to the topic?

Table 4 shows the frequency distribution of publications in different journals according to Bradford's Law (Bradford, 1934), which is used to identify the most important journals related to a specific topic. According to the bibliometric analysis carried out, this table presents the 13 most important journals related to the research topic. These journals are significant because they publish the largest number of relevant articles in the field of study. It can also be seen that the journals that have published the most on the influence of mathematical optimization on machine learning and that are identified as the most important and central in the field due to their high frequency of publications are: IEEE ACCESS, with a frequency of 4, followed by Computers and Operations Research, with a frequency of 3, then Computers and Chemical Engineering, European Journal of Operational Research, Expert Systems with Applications, Mathematical Programming, and TOP, with a frequency of 2, and finally Advances in Radio Science, AI Magazine, Alexandria Engineering Journal, Applied Intelligence, Arthroplasty Today, and Artificial Intelligence in Medicine, with a frequency of 1.

Table 4: Top 13 specialized journals (Zone 1 Bradford's Law) (Biblometrix report processed in datawrapper)

Magazine	Frequency
IEEE ACCESS	4
COMPUTERS AND OPERATIONS RESEARCH	3
COMPUTERS AND CHEMICAL ENGINEERING	2
EUROPEAN JOURNAL OF OPERATIONAL RESEARCH	2
EXPERT SYSTEMS WITH APLICATIONS	2
MATHEMATICAL PROGRAMMING	2
TOP	2
ADVANCES IN RADIO SCIENCE	1
AI MAGAZINE	1
ALEXANDRIA ENGINEERING JOURNAL	1
APPLIED INTELLIGENCE	1
ARTHROPLASTY TODAY	1
ARTIFICIAL INTELLIGENCE IN MEDICINE	1

These data are corroborated by Figure 4, which shows the graphical behavior of Bradford's Law applied to the subject under study (Brookes, 1969). The graph illustrates that the journals IEEE ACCESS and Computers and Operations Research are located in Zone 1 and at the highest point, that is, at the core of the journals specializing in the subject. Likewise, Figure 4 shows that there are few journals located in Zone 1, but they contain most of the articles published on the subject of study, while Zones 2 and 3 contain journals with fewer articles each.

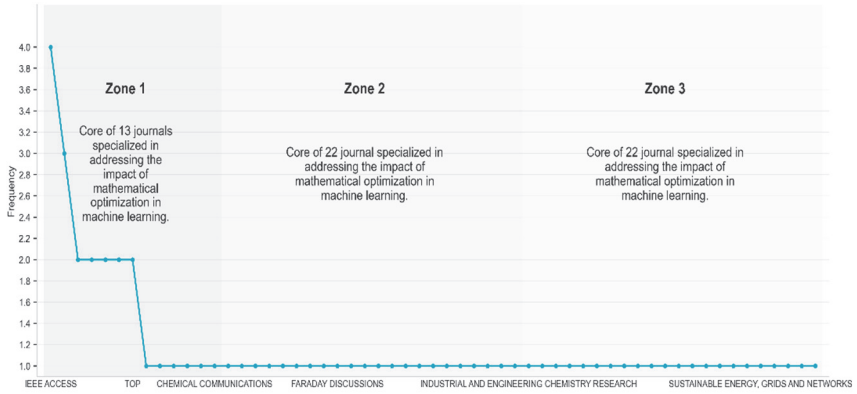


Figure 4: Ley de Bradford (Reporte Biblometrix procesado en datawrapper)

This distribution is consistent with Bradford's Law, which describes how a small number of journals concentrate most of the scientific literature in a given field. Bradford's Law indicates that these journals are found in Zone 1 with a cumulative frequency of 23 articles, at the core of the 57 journals specializing in the application of Mathematical Optimization in Machine Learning. In summary, the most important journals related to the subject of study, based on publication frequency, are IEEE ACCESS and Computers and Operations Research, followed by other journals listed in Table 4. The location of these journals in Zone 1, according to Bradford's Law, means that they are essential for the dissemination of knowledge in this subject area. Figure 4 confirms this argument by showing that these journals are located at the core of the thematic distribution.

What levels of collaboration have there been among authors, institutions, countries, etc.?

The levels of collaboration between authors, institutions, and countries show significant differences in terms of influence and scope as shown in figure 5. Authors such as Carrizosa E. and Romero Morales D. stand out for their high level of collaboration, with six joint publications, while others, such as Lee M. and Yu G., have more moderate contributions with three publications each. At the institutional level, the Institute of Mathematics at the University of Seville emerges as a key hub, with at least three relevant collaborations, followed by institutions such as the Copenhagen Business School, which play more secondary roles (Carrizosa et al., 2024). These interactions reflect the dynamics of international research networks where some actors concentrate strategic collaborations while others participate peripherally (Jiménez-Cordero et al., 2022). Furthermore, the collaboration patterns observed coincide with previous studies that highlight the importance of leading academic institutions in promoting joint research with global impact (Lee et al., 2020).

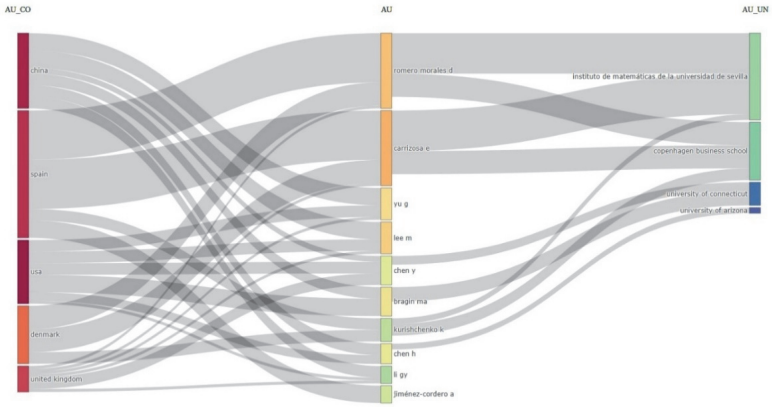


Figure 5: Levels of collaboration among authors, institutions, and countries.

Once the collaborations have been identified, the following question is pertinent:

What institutions have acted as funders of studies related to the phenomenon?

Figure 6 shows the institutions that have funded research related to this topic. The National Science Foundation (NSF) stands out as the main source of funding, with the largest number of documents. In second place is the National Natural Science Foundation of China, followed by the European Commission and the Horizon 2020 program, both with a similar number of documents. In fourth place is the Regional Government of Andalusia, followed by the Engineering and Physical Sciences Research Council, which has also funded a significant number of studies.

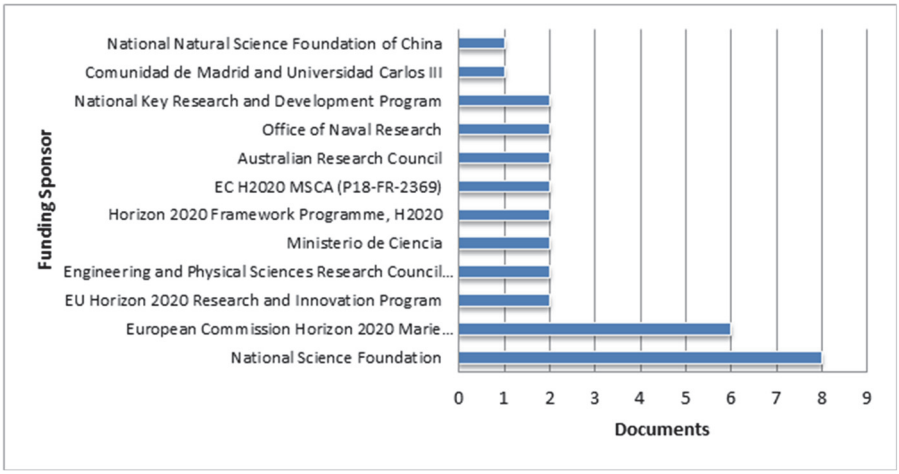


Figure 6: Research funding institutions (Scopus Report)

Other institutions that have provided funding to a lesser extent include the Japan Society for the Promotion of Science, the Ministry of Science and Innovation, the Ministry of Science, Innovation, and Universities, the National Key Research and Development Program of China, and the U.S. Department of Energy. With less participation are the European Research Council, the Ministry of Science and Technology of the People's Republic of China, the Office of Naval Research, and the U.S.

Department of Defense. In addition, several other institutions have contributed funding on a smaller scale.

What is the semantic development around the phenomenon under study?

Figure 7 shows a multiple correspondence analysis (MCA) that allows us to explore how the meaning associated with the phenomenon studied has evolved, highlighting important thematic groupings.

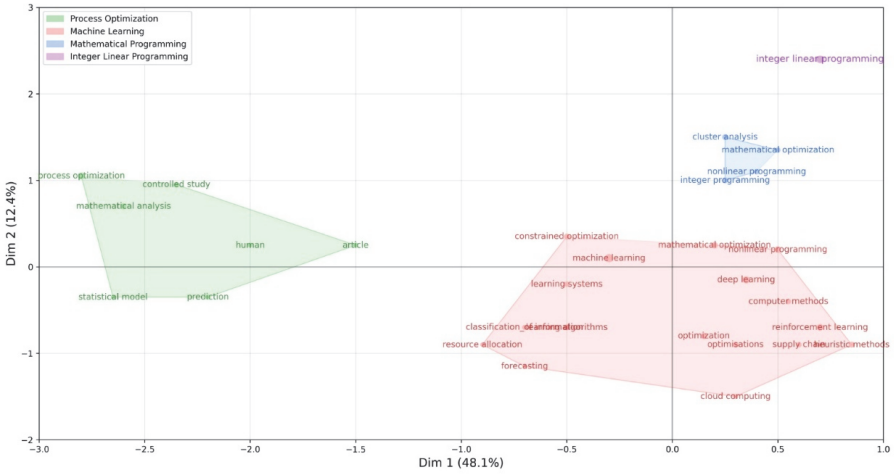


Figure 7: Semantic map on Mathematical Optimization in Machine Learning (Biblometrix Direct Report)

In the green region, we find concepts such as “process optimization,” “mathematical analysis,” “statistical model,” and “prediction.” This group reflects a preference for quantitative methods and predictive tools applied to well-defined problems. Controlled studies and the use of mathematical models focused on specific processes predominate here.

The Red region is dominated by concepts such as “machine learning,” “deep learning,” “reinforcement learning,” and “cloud computing,” reflecting the prominence of advanced artificial intelligence and computational optimization techniques, with machine learning standing out as a necessary tool for addressing complex problems in technology.

In the blue region, terms such as “cluster analysis” and “integer programming” stand out, indicating a specialized focus on computational methods and statistical analysis, mainly applied to optimization problems.

Finally, the purple region features the concepts of “integer linear programming,” highlighting an important role in solving linear optimization problems.

This analysis shows a clear evolution: we are moving from more traditional and controlled approaches, focused on mathematical models, to modern methodologies based on artificial intelligence and advanced optimization. This reflects a significant change in the way challenges in this field are addressed.

What are the driving themes surrounding the phenomenon under study, including perspectives, niches, and emerging themes?

Figure 8 shows structural thematic map that illustrate the relationship between concepts linked to the context of mathematical optimization and machine learning. This map, generated by Bibliometrix and processed by Datawrapper, reveals a strong connection with fields such as operations research, artificial intelligence, and data science.

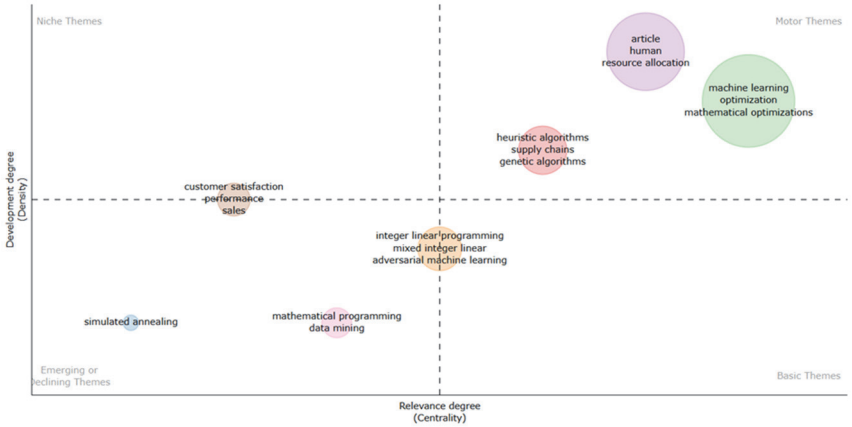


Figure 8: Structural thematic map (Direct Report from Bibliometrix)

The X-axis shows the centrality that defines the relevance of a topic, while the Y-axis shows the density and reflects the level of development of a topic through the amount of existing research. The four quadrants identified contain "driving topics," which are highly relevant and developed, as well as emerging areas such as machine learning and optimization, pointing to the importance of mathematical optimization for the development of machine learning algorithms; techniques such as machine learning and mathematical optimizations are central; the allocation of human resources suggests that optimization is applied to improve efficiency in human resource management.

"Niche themes," which are highly developed but less central, such as customer satisfaction and performance, indicate that optimization is applied to improve business results. However, despite their development, these areas remain relatively peripheral due to limitations in the availability of domain-specific data, the complexity of measuring qualitative outcomes such as satisfaction, or the interdisciplinary nature of the research required, which can present integration challenges (Cuesta-Valiño et al., 2024; Park et al., 2018). This could explain why customer satisfaction and human resources, although promising, remain largely unexplored in optimization studies.

"Basic themes," which are relevant but less developed, such as linear programming, mathematical programming, and data mining, which allows valuable information to be extracted from large data sets, are the theoretical and methodological foundations on which many optimization techniques are built, essential for modeling and solving optimization problems.

Based on this map, we can infer that mathematical optimization and machine learning are closely related and, as practical applications, optimization is used in various areas such as human resource management, business process improvement, and strategic decision-making. Likewise, the combination of optimization and machine learning is a growing trend, with a focus on more complex problems and larger data volumes.

What are the historical roots of the central concept or construct of the topic under study?

Mathematical optimization, applied to machine learning (ML), holds great importance, which is manifested through various studies (see Figure 9).

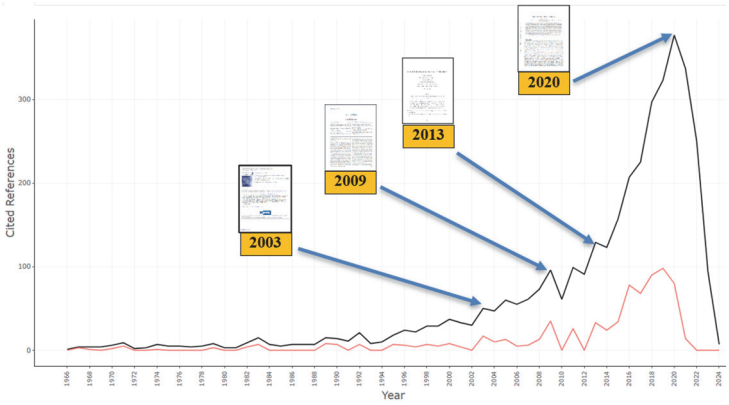


Figure 9: Spectroscopy of the year of the cited reference (historical roots of the topic)
Note. Bibliometrix report adapted by authors

The development of scientific knowledge about the influence of mathematical optimization on machine learning is the result of many studies (see Figure 9), which have contributed significantly to its evolutionary understanding and theoretical development.

This research used the Spectroscopy method from the year of the cited reference to examine the historical evolution of concepts related to the influence of mathematical optimization on mathematics learning

This quantitative methodology allows us to visualize how publications influence each other over time. By identifying the most connected nodes in these networks (i.e., the most cited publications), we can reveal the pioneering works that have laid the foundations for current knowledge.

In 2003, numerous publications were produced, notably Bart Baesens, Rudy Setiono, Christophe Mues, and Jan Vanthienen in their article Using neural network rule extraction and decision tables for credit-risk evaluation management; addressed the importance of neural networks due to their high capacity for making predictions in decision-making. The article studied three real data sets applying neural network techniques, providing valuable information for risk managers. In conclusion, the use of neural network techniques allows predictive information to be obtained for better decision-making in credit risk management.

In 2009, the book "The Elements of Statistical Learning: Data Mining, Inference, and Prediction" by Trevor Hastie, Robert Tibshirani, and Jerome Friedman was published in the journal Biometrics Oxford Academic. This book is an important reference, dealing in depth with learning techniques applying statistical methods and mathematical optimization methods for machine learning, as well as presenting updated tools and techniques that allow valuable and useful information to be extracted for those venturing into machine learning.

In 2013, Carrizosa and Romero, in their article Supervised Classification and Mathematical Optimization, explain how data mining and supervised classification are closely linked to mathematical optimization, as well as how machine vector techniques and mathematical optimization contribute to machine learning in problem solving by allowing variables to be selected and improving data interpretation.

In 2020, Velibor V. Mišić, in his research Optimization and Tree Sets, explains that machine learning models that use techniques based on tree sets, random forests, and boosted trees are efficient in their ability to predict and apply in business analysis. This study raises certain optimization problems through a mixed integer programming approach and proposes scalable solutions, such as Benders' evaluation and an iterative constraint method, applied in real-world situations.

This research has contributed to spectroscopic analysis, exploring the deep interconnection between mathematical optimization and machine learning. Important work has driven the development of machine learning algorithms, revealing how optimization has been a key catalyst in this field.

Other institutions that have provided funding to a lesser extent include the Japan Society for the Promotion of Science, the Ministry of Science and Innovation, the Ministry of Science, Innovation, and Universities, the National Key Research and Development Program of China, and the U.S. Department of Energy. With less participation are the European Research Council, the Ministry of Science and Technology of the People's Republic of China, the Office of Naval Research, and the U.S. Department of Defense. In addition, several other institutions have contributed funding on a smaller scale.

4. Discussion

The results of our study reveal exponential growth in scientific output on mathematical optimization in machine learning since 2019, with a peak in 2023. This pattern aligns with the trend identified in the work of Liu et al. (2024), who highlight the importance of optimization for solving complex problems such as industrial task scheduling, a finding consistent with the proliferation of practical applications identified in our analysis.

In terms of scientific collaboration, our finding of 97% co-authorship and strong internationalization is consistent with the studies by Rodrigues et al. (2024), who emphasize the need for global collaborations to address complex problems such as the generation of optimal molecules in the chemical industry, as this level of collaboration reflects the interdisciplinary nature of the field, facilitating the transfer of knowledge between seemingly disparate domains.

Another discovery was made in the journals with the highest number of publications on the subject, identifying IEEE Access and Computers and Operations Research as the most influential, which is consistent with the distribution observed in Bradford's Law. This is in line with other research, such as the work of Kreikemeyer et al. (2023), which emphasizes the importance of journals as platforms for important research in mathematical optimization applied to machine learning.

In addition, semantic analysis suggests a transition toward more advanced topics, such as deep learning and integer-based optimization, a result that also aligns with the observations found by Misener and Biegler (2023), who showed that models based on mathematical optimization and machine learning are transforming chemical processes, an emerging topic highlighted in the thematic map.

Differences are also identified in niche and emerging topics, such as customer satisfaction and data mining, which, although they have seen significant developments, remain under-explored. In this regard, research such as that of Carrizosa et al. (2024) proposes innovative approaches to interpretation and decision-making, providing an opportunity to expand research in these areas.

Despite their growth, these areas remain marginal in the field, possibly due to factors such as the scarcity of contextual data and variables for assessing qualitative variables such as satisfaction, and the challenges posed by the interdisciplinary collaboration needed to address these issues comprehensively (Cuesta-Valiño et al., 2024; Park et al., 2018). These limitations may contribute to areas such as customer satisfaction and human resource management, despite their potential, remaining underaddressed in optimization studies.

Based on the above, this research provides evidence of the influence of mathematical optimization applied to machine learning, highlighting its multidisciplinary nature. However, it has limitations such as the use of a single database (Scopus) to perform the bibliometric analysis, which could exclude relevant research published in other databases. This is an opportunity for future research, which could expand this analysis by incorporating additional databases and exploring the application of optimization in specific domains such as healthcare, achieving a more comprehensive understanding of the influence of mathematical optimization on the development of artificial intelligence.

As for the academic implications, the main theoretical contributions are presented below.

5. Theoretical Implications

The findings obtained in this bibliometric study allow us to identify several theoretical implications that contribute to the understanding of the impact of mathematical optimization in the field of machine learning. First, the exponential growth of scientific production since 2019 suggests a theoretical consolidation of the link between the two disciplines, reflecting not only an increase in the amount of research, but also a growing conceptual and methodological maturity.

Likewise, semantic and thematic analysis evidences an evolution in theoretical approaches, transitioning from traditional models centered on linear programming and process optimization, to contemporary approaches based on deep learning, integer optimization and cloud computing. This transition suggests a paradigm shift in the way complex problems are approached, positioning mathematical optimization as a key tool in the design of more efficient and robust algorithms in machine learning.

From an epistemological perspective, the high interdisciplinarity and intense international collaboration observed (97% co-authorship and 46% international co-authorship) reveal that knowledge in this area is built collectively, crossing both disciplinary and geographical boundaries. This strengthens the theoretical base by incorporating conceptual frameworks from fields such as operations research, artificial intelligence, statistics and computational engineering.

On the other hand, the application of bibliometric laws such as those of Lotka and Bradford not only made it possible to characterize the productivity and distribution of knowledge, but also evidenced the existence of consolidated theoretical nuclei and emerging lines with high potential for development, such as customer satisfaction, data mining and the allocation of human resources through optimization techniques.

Overall, the results indicate that mathematical optimization not only acts as a methodological support for machine learning, but also generates new theoretical perspectives that enrich the understanding of complex problems and promote greater integration between theory and practice in artificial intelligence. This convergence represents a turning point for future research, which could further explore the philosophical, methodological and applied implications of this integration.

6. Practical Implications

The results of this bibliometric review offer important practical implications for researchers, technology developers, public policy makers and companies implementing AI-based solutions. The consolidation of the link between mathematical optimization and machine learning not only represents a theoretical evolution, but also transforms the way practical solutions are designed and implemented in real-world contexts.

First, the increasing adoption of optimization techniques, such as integer programming, evolutionary algorithms and gradient descent, has been instrumental in improving the performance of machine learning models, making them more efficient, accurate and adaptive. This finding is especially relevant for sectors that handle large volumes of data and need to make real-time decisions, such as healthcare, manufacturing, finance or logistics.

The identification of driving themes in the structural thematic map - such as human resource allocation and process improvement - suggests that mathematical optimization has not only technical but also managerial applications. This implies that organizations can directly benefit from integrating these models into strategic planning, operations optimization and data-driven decision making.

On the other hand, the broad international collaboration and funding from high-level institutions, such as the National Science Foundation or the European Commission, reveal that the applications of this synergy are global and receive strong institutional support. This represents a concrete opportunity for researchers and companies seeking funding for applied projects in optimized artificial intelligence.

In addition, the growth of research in specialized journals located in the central zone according to Bradford's Law -such as IEEE Access or Computers and Operations Research- offers practitioners clear guidance on the most relevant channels to disseminate, consult and implement practical innovations in the area.

Finally, the emergence of topics such as customer satisfaction and data mining within the ecosystem of optimization applied to machine learning opens new avenues for application in non-traditional fields. This development encourages professionals from diverse disciplines to view these techniques as accessible, science-based tools for addressing real-world problems.

Overall, this review shows that the interaction between mathematical optimization and machine learning is not only a field of academic interest, but a driver of technological transformation with tangible effects in multiple industries and social contexts.

7. Conclusion

The bibliometric review reveals a growing trend in publications on the influence of mathematical optimization in machine learning, particularly since 2019. This reflects the increasing scientific interest in the topic, which is closely linked to recent advancements in machine learning and the need for mathematical solutions that enhance algorithm accuracy and productivity. These solutions enable the resolution of complex problems while minimizing computational resource consumption, including memory, disk space, and processing time.

Regarding key researchers in this field, a small group, including Carrizosa and Romero Morales, has demonstrated a significant influence through international collaborations and publications in high-impact journals. Their work highlights the interdisciplinary nature of the research, fostering active collaboration between different disciplines and countries. This global and interdisciplinary approach strengthens knowledge transfer and the development of practical applications. The collaboration among authors and institutions underscores the international scope of this research field, showcasing the establishment of scientific networks aimed at addressing complex challenges and conducting high-impact studies.

The most relevant specialized journals identified were *IEEE Access* and *Computers and Operations Research*, which serve as essential platforms for disseminating knowledge in this field. This finding is supported by Bradford's Law, which states that a small core of publications concentrates most scientific advancements, facilitating access to high-quality research.

Additionally, the semantic analysis reveals a transition from traditional methods to advanced approaches, with *deep learning* and mathematical optimization emerging as central themes at the core of the research. Meanwhile, niche topics present opportunities for expanding knowledge in areas such as *data mining*, *mixed-integer linear programming*, and *strategic decision-making*, alongside emerging themes like *customer satisfaction*.

Regarding historical foundations, the analysis highlights the influence of pioneering studies that have shaped theoretical frameworks and applied advanced techniques in practical domains. These contributions have solidified mathematical optimization as a fundamental component in the advancement of machine learning, reinforcing its significance in the development of cutting-edge technological solutions.

As for the patterns and trends in scientific production concerning the influence of mathematical optimization on machine learning, key observations include an exponential increase in recent research, a high level of international collaboration, and the concentration of knowledge in specialized journals. These factors underscore the interdisciplinary and global nature of the field, as well as its evolution toward advanced methodological approaches and practical applications that continue to redefine the boundaries of artificial intelligence.

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