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RESEARCH ARTICLE

Unleashing the Potential of Blockchain and Machine Learning: Insights and Emerging Trends From Bibliometric Analysis

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ABSTRACT Blockchain and machine learning (ML) has garnered growing interest as cutting-edge technologies that have witnessed tremendous strides in their respective domains. Blockchain technology provides a decentralized and immutable ledger, enabling secure and transparent transactions without intermediaries. Alternatively, ML is a sub-field of artificial intelligence (AI) that empowers systems to enhance their performance by learning from data. The integration of these data-driven paradigms holds the potential to reinforce data privacy and security, improve data analysis accuracy, and automate complex processes. The confluence of blockchain and ML has sparked increasing interest among scholars and researchers. Therefore, a bibliometric analysis is carried out to investigate the key focus areas, hotspots, potential prospects, and dynamical aspects of the field. This paper evaluates 700 manuscripts drawn from the Web of Science (WoS) core collection database, spanning from 2017 to 2022. The analysis is conducted using advanced bibliometric tools (e.g., Bibliometrix R, VOSviewer, and CiteSpace) to assess various aspects of the research area regarding publication productivity, influential articles, prolific authors, the productivity of academic countries and institutions, as well as the intellectual structure in terms of hot topics and emerging trends. The findings suggest that upcoming research should focus on blockchain technology, AI-powered 5G networks, industrial cyber-physical systems, IoT environments, and autonomous vehicles. This paper provides a valuable foundation for both academic scholars and practitioners as they contemplate future projects on the integration of blockchain and ML.

INDEX TERMS Blockchain, machine learning, bibliometric analysis, network visualization.

I. INTRODUCTION

Over the past few decades, several game-changing technologies have emerged, including big data, the Internet of Things (IoT), AI, and blockchain. Among these technologies, blockchain has become a buzzword, gaining widespread attention and recognition in industry and academia alike. As one of the most hyped innovations, blockchain has the potential to revolutionize business models, financial transactions, and management processes across various industries in the coming years [1]. The emergence of Bitcoin, released by the pseudonymous [2], has led to a surge in public interest in blockchain technology. This innovative technology serves as the underlying architecture that maintains the ledger of transactions. At its core, blockchain is a distributed ledger that enables secure and transparent transactions without the

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need for a fully trusted third party [3]. The blockchain operates as a decentralized database, wherein all transactions are recorded in a chronological and immutable manner. Each block in the chain holds a cryptographic hash of the preceding block, which ensures the integrity of the ledger and makes any unauthorized modification or data tampering highly unlikely [4]. Furthermore, the peer-to-peer network utilizes consensus algorithms to authenticate transactions, obviating the necessity of a centralized authority to approve them. Based on the core characteristics of transparency, decentralization, persistency, anonymity, and auditability, blockchain applications provide breakthrough and innovative solutions that can significantly reduce costs and improve efficiency. The rise of blockchain, especially its dominant application, Bitcoin, has ignited a public discourse on the potential impact of the swiftly developing technology. Its broad implications extend beyond solely cryptocurrency applications and affect numerous industries. Several implementations of blockchain technology are extensively used in modern-day business, ranging from the IoT [5], insurance, and finance to supply chain management [6], healthcare, and electoral voting [7].

The emergence of ML as a sub-field of AI has led to significant disruptions across a variety of domains in daily life. It is concerned with the development of algorithms and models that can be trained on large datasets to make predictions, identify patterns and relationships, and automate decision-making processes. The roots of ML can be traced back to the 1950s, when [8] proposed the idea of machines that can learn and become artificially intelligent. The ability of computers to make predictions or decisions that resemble human behavior for real-world problems, both in industry and daily life, has sparked human interest in the fields of ML and AI [9]. Since its inception, ML has experienced a surge in popularity due to the availability of vast amounts of data produced daily by end-users and advancements in computing technology. It has been successfully applied across diverse fields such as image and speech recognition, natural language processing, recommendation systems, and predictive analytics.

The combination of blockchain and ML holds an enormous opportunity to introduce novel decentralized applications and services that were previously unattainable [10]. Although blockchains and ML have notable technological differences, they can be integrated to address their respective bottlenecks and create a synergetic effect by bridging these two ecosystems. The combination of blockchain and ML harbors great promise for a wide range of applications, including fraud detection, supply chain management, healthcare, and decentralized finance (DeFi). One potential use case for combining blockchain and ML could be observed in the realm of decentralized autonomous organizations (DAOs), which are decentralized entities that can leverage ML models to quickly and automatically validate transfers of data, value, or assets among stakeholders on the blockchain [11]. For example, a DAO could use ML to predict the market demand for a product, and then use blockchain-based smart contracts to automatically adjust the supply of that product accordingly. Recently, there have also been attempts to leverage blockchain to enhance ML applications. One such application is to secure data sharing, which involves model training and data privacy preservation. Blockchain provides a tamper-proof record of data provenance and access control, which can be utilized for this purpose [12]. In addition, the decentralized nature of blockchain networks can enable multiple parties to contribute data and resources to train an ML model, which can improve the accuracy and robustness of the model. Overall, the list of possible combination applications is not exhaustive; the possibilities are endless and are continuously explored by researchers and practitioners around the world.

Bibliometrics is a field of study within library and information science that involves the use of quantitative techniques to investigate the characteristics and patterns of bibliographic data [13]. By examining the intrinsic relationships between publications, this approach provides a unique perspective for assessing and evaluating scientific output [14]. In essence, bibliometrics aims to quantify the impact of research and its dissemination by measuring aspects such as the number of publications, citations, and the impact of individual authors or journals within a given field [15]. The present study endeavors to employ bibliometric analysis using tools such as the Bibliometrix R package, VOSviewer, and CiteSpace software to systematically examine the literature on the combination of blockchain and ML. The analysis within the current study seeks to comprehensively elucidate the current state of research, identify hot topics, reveal trends and potential patterns, and establish relationships among scholarly publications. This paper aims to analyze 700 articles gathered from the Web of Science (WoS) core collection database to address specific research questions that require attention:

RQ1. How has the research on the integration of blockchain and ML evolved over time?

RQ2. What is the current performance status for the key constituents (authors, institutions, countries) in the research output on blockchain and ML integration?

RQ3. Which are the most prominent journals used to disseminate knowledge in relevant literature?

RQ4. Which are the most influential publications related to the research field?

RQ5. What are the hotspots in the literature and emerging trends that warrant future research?

Henceforth, the remainder of this paper is structured as follows: Section II provides a brief overview of existing literature reviews. Section III outlines the data source and methodology of this study. Section IV explores the patterns and dynamics of the research field. Section V concludes the paper by discussing the main contributions and limitations of the study, as well as promising areas for future research agendas.

TABLE 1. Contrasting the current investigation with existing literature reviews in the research field.

Ref.	Scope	Review type	Database	Dataset	Time span	Key findings
[16]	Investigate the revolutionary implications of integrating blockchain and AI technologies.	Critical Review	Scopus	121	2012-2022	The potential use cases for integrating blockchain and AI within supply chains, financial services, healthcare, life sciences, smart grids, agriculture, and the Internet of Things (IoT).
[17]	Examine the applications of combined blockchain and AI platforms in health record management systems (EHRs).	Systematic Literature Review (SLR)	Multiple	189	-	The role of blockchain for timestamping healthcare records, providing secure and tamper-proof systems, and the patient data exchange accuracy utilizing AI methods.
[10]	Provide a three-part classification to categorize the various ways in which blockchain and AI can be linked.	Systematic Literature Review (SLR)	Multiple	32	-	Three main perspectives of potential AI and blockchain synergies: (i) How AI can be used for blockchain. (ii) How blockchain can be used for AI. (iii) How blockchain can coexist alongside AI.
[18]	Discuss the implementation of blockchain and ML in the intelligent healthcare sector.	Bibliometric Review	WoS	112	2014-2022	Perspectives of the current state of research across various countries, institutions, authors, journals, subject areas, and research hotspots.
[19]	The practical implementations of AI and blockchain convergence for business processes.	Bibliometric-content Review	Scopus	872	2017-2020	Analysis of the productivity of publications related to the integration of AI and blockchain in business, including trends by year, influential articles, popular topics and co-occurrences, intellectual structure, and its major thematic clusters.
This study	Survey the potential of combined blockchain and ML.	Bibliometric Review	WoS	700	2017-2022	Findings pertaining to the patterns in publications, leading authors, countries/institutions, and most influential publications, as well as the intellectual structure of the field, and thematic clustering.

II. RELATED WORK

As the research interest in blockchain and ML expands, it becomes essential to conduct a thorough examination of the current literature to determine any research gaps. The screening of these gaps can then be leveraged to create opportunities to strengthen the current study. Although a significant number of literature reviews have been conducted on the convergence of blockchain and ML, these reviews have several limitations that this paper aims to address. For example, in a recent systematic literature review by [17], a total of 189 research papers from various sources were examined. The focus of the review was on the amalgamation of blockchain technology and ML to enhance health record management systems. The authors found that by leveraging blockchain technology, health record management systems could benefit from enhanced decentralization, security, and privacy, which were often lacking in traditional Electronic Health Records (EHRs). In his study, [10] made a valuable contribution to the research on the integration of blockchain and AI by presenting a thorough analysis of existing scientific publications and classifying the possible ways to combine these technologies into three categories. The research encompassed all possible combinations (i.e., blockchain for AI, AI for blockchain, and blockchain and AI alongside) and provided an overview of the potential benefits and applications of such combinations. Taherdoos [16] conducted a meticulous evaluation of publications on the combination of blockchain and AI that were released between 2012 and 2022. The survey aimed to analyze the present status of the integration of blockchain and AI, the applications of this combination, and the potential benefits and revolutionary implications of utilizing these technologies together. Moreover, the study addressed the gaps and significant barriers to the successful integration of blockchain and AI.

However, certain review studies have explored the amalgamation of blockchain technology and ML through a bibliometric mapping approach. For instance, [18] performed a bibliometric analysis of 112 articles retrieved from WoS to examine the collaborative use of blockchain and ML in the smart medical industry. The authors utilized a keyword analysis technique to classify the literature into five distinct research clusters, comprising ML, AI, blockchain, sensors, and IoT, to discern the most recent research trends in this domain. Likewise, [19] conducted a bibliometric-content analysis of 872 articles sourced from Scopus to investigate the applications and advantages of integrating AI and blockchain platforms for businesses. This study employed a thematic analysis approach and identified four primary thematic clusters, which included supply chains, healthcare, secure transactions,finance, and accounting. By providing an intellectual structure of the subject, the research established key insights into the topic.

Notwithstanding that several reviews have endeavored to provide a comprehensive perspective on the existing knowledge, relying solely on Systematic Literature Reviews (SLRs) might not be the most suitable approach. SLRs can be vulnerable to bias, are more time-intensive compared to other types of reviews, and may be challenging to employ when scrutinizing a large volume of literature sources [20]. Moreover, current bibliometric studies investigating this

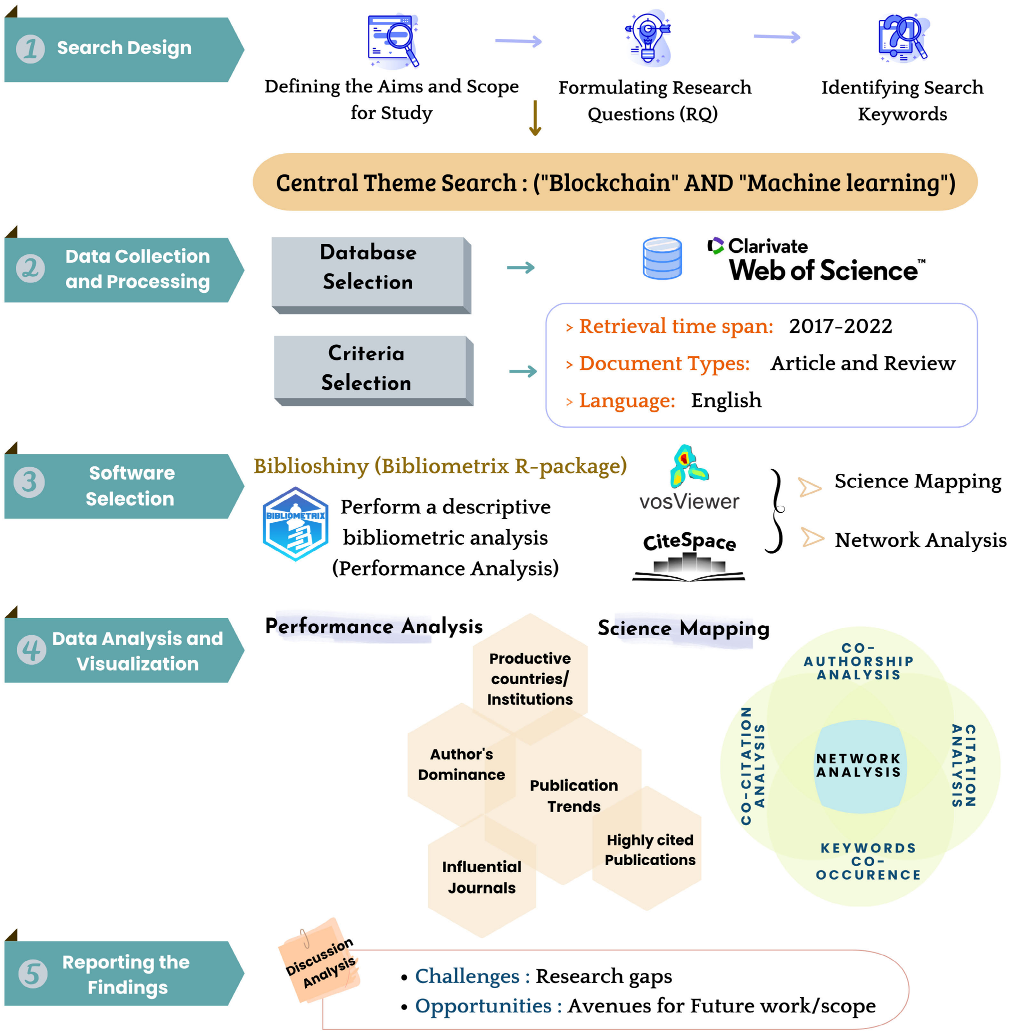

FIGURE 1. A structured methodology for conducting bibliometric analysis.

research area are either based on a limited number of articles or adopt different bibliometric techniques, resulting in varying insights and clustering outcomes. Therefore, to overcome these shortcomings, the present research is an important endeavor that aims to provide a scientific overview of the current literature on the incorporation of blockchain and ML through bibliometric visualization. This research marks a significant milestone and a landmark contribution toward enhancing researchers' and practitioners' grasp of the interrelationship between blockchain and ML. Table 1 compares the extent, approach, and substantial contribution of this review to previous studies.

III. MATERIALS AND METHODS

The present study combined bibliometric analysis and the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) protocol to synthesize existing literature and uncover new insights. The bibliometric analysis leverages quantitative techniques on bibliometric data (e.g., units of publication and citation) to identify publication patterns and influential studies, determine current research areas, and offer insights into future prospects [21]. This widely-used method was selected to assist researchers in tracking emerging or trending topics for studies and accessing current research knowledge through the interpretation of data gleaned from academic journal publications and their citations [22].

Drawing upon the five-step structured methodology recommended by [23], the research protocol was designed to identify the most significant works in the field and, subsequently, determine the topical areas of research and potential avenues for future work. Primarily, the analysis was conducted through a comprehensive process consisting of five key stages: search design, data acquisition and processing, software selection, data analysis, visualization, and lastly, a discussion of findings. The study's approach is illustrated in Figure 1, and further details on each phase are provided in the following section.

TABLE 2. Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Papers written in English	Papers not written in English
Papers published from 2017 to 2022	Papers without abstract
Papers published in peer-review journals	Duplicated papers
Research or review papers	Book, book chapter, book review, conference proceedings paper, and the editorial material
Keywords included in the article's title, abstract, or keywords	Title and Abstracts that deviated from our research scope
Papers mainly focused on the investigation of blockchain and ML convergence and proposing blockchain-ML based applications	Papers that are irrelevant to the research focus: the main topic of the papers involved only either one of the two technologies, not both

A. SEARCH DESIGN

To build a research protocol, it is crucial to begin by crafting research questions, selecting relevant keywords, and establishing specific criteria for including or excluding research studies. This phase is pivotal since it sets the framework for how the literature search, data extraction, screening, and analysis will be performed. The current study sought to examine the bibliometric and intellectual structure of the literature on the integration of blockchain and ML. Thus, the search terms ''blockchain'' and ''machine learning'', were chosen to sift through the literature that pertains to the subject matter.

B. DATA COLLECTION AND PROCESSING

1) DATABASE

Currently, Web of Science and Scopus are the most commonly used literature databases across various disciplines. For this study, the original literature database was sourced from the Web of Science core collection. This database was selected due to its comprehensive coverage of over 18,000 high-quality journals across various fields, as well as its vast collection of 1.3 billion citations dating back to 1900 [24]. Web of Science, owned by Clarivate, has become a widely recognized platform for searching scientific citations, discoveries, and analytical information. It is leveraged by academic libraries as a research tool and provides a rich dataset for large-scale, data-intensive studies in various academic fields [25]. Moreover, the database includes millions of bibliographic records, billions of citation connections, and metadata fields such as authors, affiliations, keywords, and cited references for each publication.

2) SELECTION CRITERIA

To align with the interest of this research, the scope was restricted to peer-reviewed research articles and reviews about the integration of blockchain technology and ML, published between 2017 and 2022. These sources were considered the most reliable for this study. To refine the literature search, any papers that met the following criteria were excluded: (i) not written in English; (ii) published in conference proceedings, books, book chapters, or editorial materials; (iii) deemed irrelevant to the current study. Table 2 provides a synoptic overview of the applied screening criterion.

TABLE 3. Search strategy and data retrieval process.

Retrieval date	Database	Search statement
20-11-2022	WoS core collection	**#1** TS= (“Blockchain” OR “Block chain” OR “Block-chain” OR “Distributed Ledger” OR “Hyperledger” OR “Smart contract”) **AND** TS=(“Machine Learning” OR “ML” OR “Artificial Intelligence” OR “AI” OR "Deep Learning") *Result:* 2763 articles
		#2 TS= (“Blockchain” OR “Block chain” OR “Block-chain” OR “Distributed Ledger” OR “Hyperledger” OR “Smart contract”) **NEAR/50** TS=(“Machine Learning” OR “ML” OR “Artificial Intelligence” OR “AI” OR "Deep Learning") *Result:* 1763 articles

3) DATA SCREENING

The survey of the scientific publications relevant to the search terms ''Blockchain Technology'' and ''Machine Learning'' was carried out in November 2022 based on the aforementioned database and screening criteria. However, the data gathering protocol followed a broader search strategy by cross-searching a comprehensive set of keywords (blockchain OR distributed ledger OR smart contract) AND (ML* OR Machine learning* OR AI), which appeared in the title (TI), abstract (AB), author keyword (AK), and keywords plus fields (KP). Table 3 summarizes the data retrieval procedure.

The initial search yielded 2763 articles, considering the period between 2017 and 2022. However, the raw data contained some irrelevant information due to the inherent drawbacks of retrieval methods and the large number of published articles having ''blockchain'' or ''machine learning'' in their topic. To address this issue, the PRISMA guidelines were applied, as introduced by [26] and updated by [27] in 2020. The purpose was to perform data cleaning, thereby guaranteeing the accuracy and consistency of the extracted datum. Adapting the PRISMA protocol to fit the procedure that has been conducted has resulted in an advantageous reduction of information bias. Congruent with the PRISMA approach, Figure 2 portrays the procedure adopted to identify, screen, and include relevant research papers for the bibliometric analysis.

In the first step of the PRISMA methodology, the initial set of publications was identified through the mere application of a search string that resulted in 2763 articles.

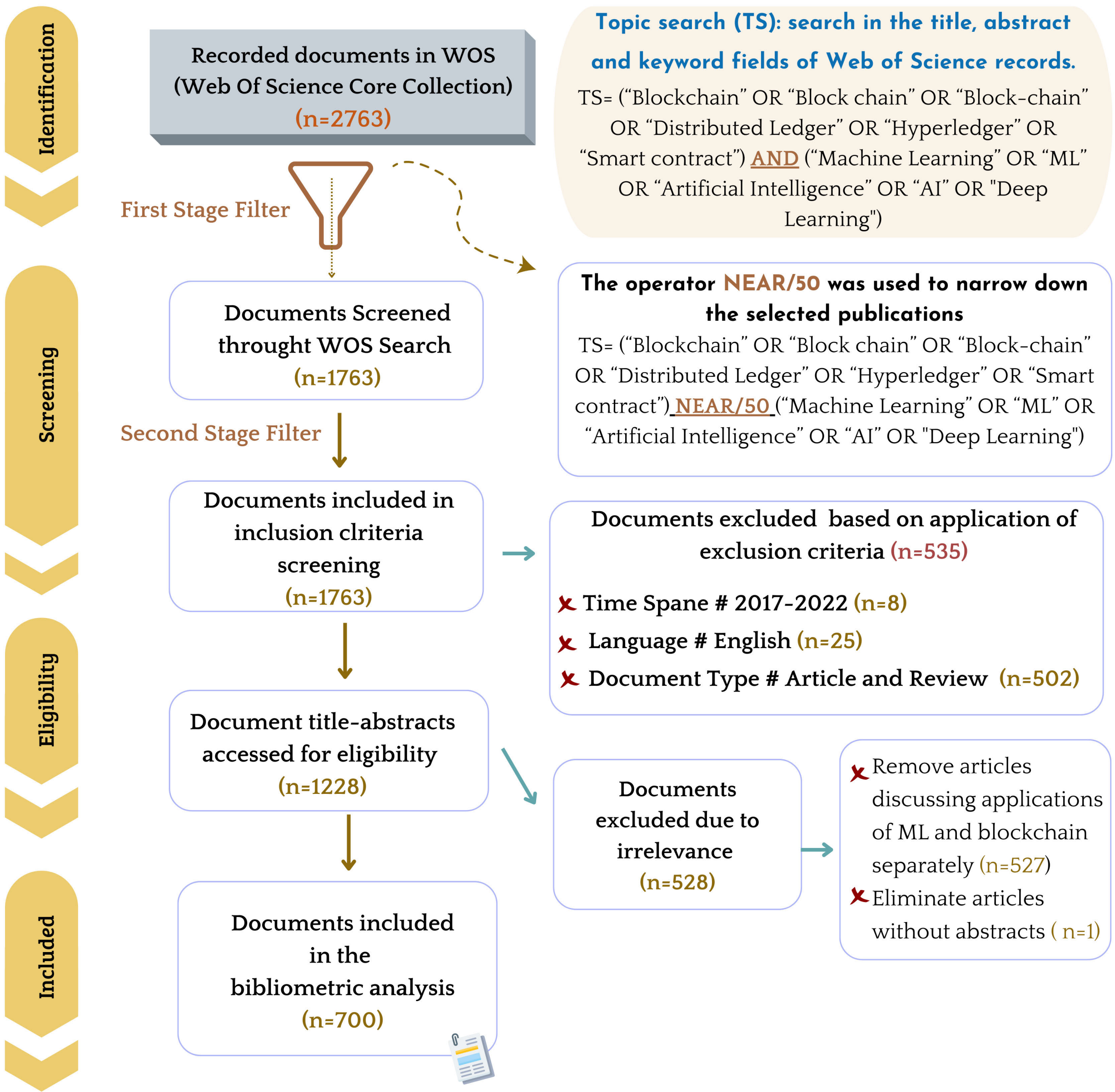

FIGURE 2. PRISMA flow diagram for identifying relevant documents included in bibliometric analysis.

To ensure that all search terms related to "Blockchain" and "Machine Learning" appeared either in the title or the same paragraph, the proximity operator "NEAR/50" was utilized, as recommended by WoS. The approach used effectively narrowed down the number of potentially relevant publications to 1763.

The screening stage involved the removal of duplicates as well as a preliminary screening to exclude documents that did not fulfill the previously established inclusion/exclusion criteria. Among the identified publications, non-English papers (n=25) were excluded, and only journal articles and reviews were considered as they represent original scientific development, leaving 1228 full-text articles that were assessed for eligibility.

The eligibility stage entailed manual title and abstract screening to further assess whether the remaining papers should be included or excluded from the analysis. This step aimed to filter out irrelevant documents and refine the research direction for greater accuracy. As a result, 528 articles were disregarded, and the database was ultimately reduced to 700 articles.

Finally, the Inclusion Stage implied exporting and analyzing the final dataset of 700 publications. To facilitate further analysis, the article data were saved in tab-delimited files in "plain text" format, which contained the "Full Record and Cite References". The exported records from WoS incorporated a wealth of information, including the article's title, author names and affiliations, publication year, journal name, citation count, and research field. These data were utilized for conducting bibliometric analysis.

C. SOFTWARE SELECTION

Conducting a comprehensive bibliometric analysis requires appropriate tools that can produce reliable research outcomes and meaningful insights from the exported dataset [28]. In light of making bibliometric analysis more accessible and user-friendly, various visual analysis tools and assistive software packages have been developed in recent years, including CiteSpace, VosViewer, Gehi, RefViz, and HistCite. The ongoing study has identified three potent and efficient visual analysis tools for bibliometric analysis: Bibliometrix, CiteSpace, and VOSviewer. These tools were capable of producing valuable insights from the retrieved bibliographic data.

Bibliometrix, developed by [29], is a freely available R-package for conducting quantitative research in bibliometrics and scientometrics. This package offers quick analysis and data matrix creation for performance analysis and science mapping of bibliographic collections, distinguishing it from other software solutions. For this study, the most recent version of Bibliometrix was utilized through its web-based application, Biblioshiny.

CiteSpace is a powerful and user-friendly Java-based software program widely utilized for bibliometric analysis in order to grasp the landscape and dynamics of scholarly literature within a particular knowledge area. The software conceived by Dr. Chen [30], a leading expert in the field of information visualization, provides a range of features for exploring and analyzing large-scale scientific literature datasets. Its most notable feature is the ability to identify and visualize patterns of co-citation and co-occurrence among scholarly publications. This allows researchers to gain insights into the structure and evolution of a particular research field, as well as identify important authors, journals, and research topics. Moreover, CiteSpace offers a range of customization options, allowing users to fine-tune the parameters of their analyses and visualizations to suit their specific research requirements.

Aside from CiteSpace, **VOSviewer**, developed by [31], is a powerful tool for constructing and displaying bibliometric networks with high quality and resolution. This software facilitates the efficient generation of scientific and knowledge maps, which can encompass journals, scholars, or academic publications. Researchers can build these maps based on citation, bibliographic coupling, co-citation, or co-authorship relationships. VOSviewer was used in the present study to produce cluster maps and visualize the co-occurrence of keywords and cooperation patterns between authors, institutions, and countries by determining their frequency and total link strength.

TABLE 4. Descriptive statistics about the publications extracted between 2017 and 2022.

Description	Results
Main information	
Documents	700
Sources (journals, books, etc.)	265
Annual Growth Rate %	169.44
Average citations per document	12.1
Average citations per year per document	0.92
References	26,205
Document type	
Article	651
Review	49
Document content	
Keywords Plus (ID)	620
Author's Keywords (DE)	1,714
Authors	
Authors	2,502
Authors of single-authored documents	39
Authors of multi-authored documents	2,463
Author's collaboration	
Single-authored docs	42
Average co-authors per document	4.54
International co-authorships %	44.57
Collaboration index [1]	3.75

D. DATA ANALYSIS AND VISUALIZATION

To elucidate the intellectual landscape of the publications retrieved and to address the research questions outlined in Section I, this study employed a two-step data analysis approach. Firstly, a **performance analysis** was conducted to map the growth patterns of publications, highlighting contributions from countries, universities, and authors, as well as the most notable journals. The performance analysis incorporated various metrics and indicators, such as the total number of publications (TP), the total number of citations (TC), and the average number of citations per publication (AC, i.e., TC/TP) [32]. Secondly, a **science mapping** approach was utilized to investigate the intellectual interactions and structural connections among research constituents (authors, countries, universities/institutes, and publications) through the construction of bibliometric maps. To uncover the intellectual connections and knowledge structure of the research studies, various methods were exploited, including co-authorship analysis, co-citation analysis, citation analysis, and analysis of co-occurring keywords. The analysis was further supported by three enrichment techniques: networking, clustering, and visualization. Ultimately, after conducting an extensive bibliometric analysis, the results of the study and their implications for future research were reported.

IV. RESEARCH FINDINGS

A. OVERVIEW OF RETRIEVED DATA

The bibliometric statistics for the intersection of blockchain and ML, obtained using the biblioshiny tool, are presented in Table 4. The search yielded a total of 700 documents

[1]The total number of authors of multi-authored articles divided by the total number of multi-authored articles.

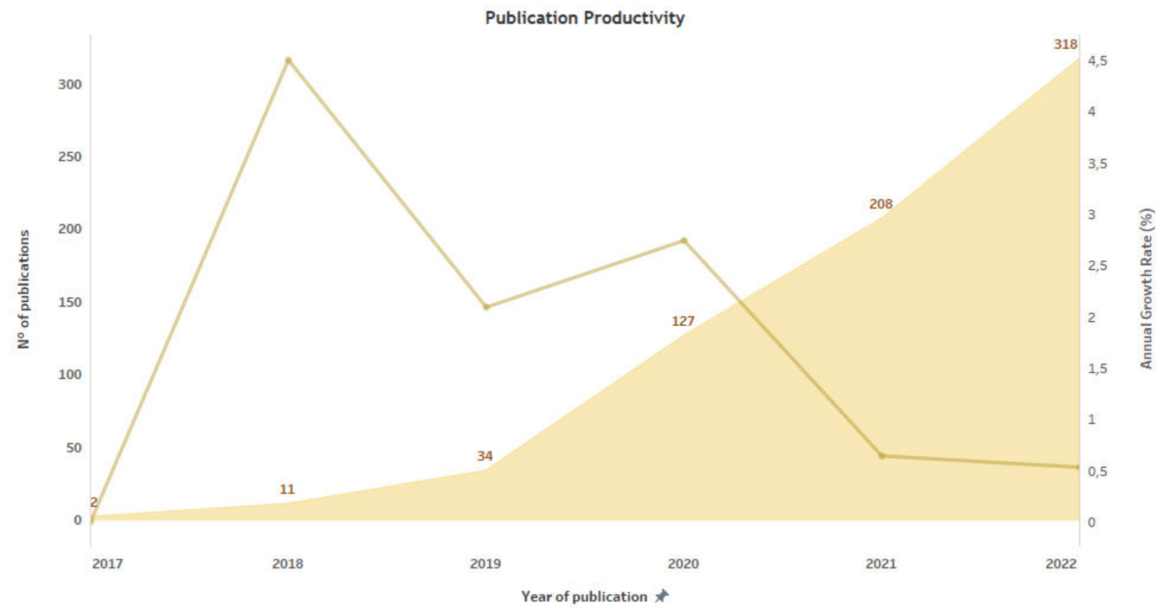

FIGURE 3. Year-wise publication growth trend of blockchain and ML-related research. The average growth rate (%) is measured as the ratio between the number of publications in two consecutive years.

from 265 sources, spanning the years 2017 to 2022. The majority of these documents ($n = 651$) were empirical research articles. On average, these articles had a citation rate of 12.1. The analysis also revealed a trend towards greater cooperation, as evidenced by the involvement of 2502 authors in the 700 publications analyzed. Among these authors, 2463 participated in research papers with multiple authors, whereas only 42 papers had a single author. The collaboration index, estimated at 3.75, highlighted the prevalence of co-authorship in the analyzed literature.

B. PERFORMANCE ANALYSIS

To evaluate the impact of research elements on the research field, a descriptive analysis known as performance analysis is conducted. This type of analysis involves examining multiple publications and journal indices to assess the effectiveness of both authors and sources.

1) PUBLICATION TRENDS

Figure 3 plots the annual distribution of the 700 papers retrieved from 2017 to 2022, providing significant insights into the evolution of research interest in the integration of blockchain and ML. The findings revealed that the number of publications was relatively low (less than 10 publications per year) in early 2017, followed by a spike in 2022, when 318 papers were released. Blockchain and ML are two hallmark technologies that emerged as early as 2016, and it is noteworthy that their integration into research only gained academic attention a year later in 2017. As the adoption of blockchain and ML-related applications grew within the scientific community, there was a significant surge in publications, particularly at the start of 2019, as shown in Figure 3. However, since 2019, the number of publications has received an exponential increase at an annual growth rate of 53%, demonstrating that the integration of blockchain and ML is an emerging research field that has garnered tremendous attention from scientists worldwide. This trend also suggests ample space for further research in this area.

2) CONTRIBUTION OF DOMINANT RESEARCH AREAS

The research area denotes the discipline categories of the published papers relevant to the study subject, classified by WoS and also known as *WoS Subject Categories*. The analysis involved 700 publications collected from WoS that were assigned to 83 different Web of Science categories, reflecting the wide range of applications within the research field. Table 5 showcases the top 10 WoS categories in which academic articles related to the research area were published between 2017 and 2022. The categories were ranked based on the total number of papers (TP) and the percentage of total papers for each category (TPR%). The analysis established a diverse array of disciplines, including Computer Science, Telecommunications, Applied Physics, and Instruments & Instrumentation, among others. "Computer Science, Information Systems" is the largest category with 298 publications. The followings are "Engineering, Electrical & Electronic" and "Telecommunications," each with over 261 and 228 publications, respectively. It merits attention to note in advance that the number of publications listed in Table 5 exceeds the sample size, and hence the overall percentage exceeds 100% since records extracted might be assigned to several different discipline categories. where TP refers to total papers, and TPR% is the percent of

FIGURE 4. TreeMap of top 10 subject categories (WoS).

TABLE 5. Breakdown of the top 10 WoS categories in the blockchain and ML-related research.

Rank	WoS Subject Category	TP	TPR%
1st	Computer Science, Information Systems	298	42.57
2sd	Engineering , Electrical & Electronic	261	37.29
3rd	Telecommunications	228	32,57
4th	Computer Science, Theory & Methods	73	10.43
5th	Computer Science, Hardware & Architecture	68	9.71
6th	Computer Science, Artificial Intelligence	47	6.71
7th	Computer Science, Interdisciplinary Applications	43	6.14
8th	Computer Science, Software Engineering	37	5.29
9th	Physics Applied	35	5
10th	Instruments & Instrumentation	32	4.57

total papers in the field. This underscores the interdisciplinary nature of blockchain-based ML research, which has evolved to encompass a broad range of domains. Besides computer science-related categories, publications in the research field were also found to be widely published in engineering, physics, and telecommunications.

Figure 4 displays a TreeMap depicting the dispersion of publications among several WoS Subject Categories. The TreeMap visualization includes both the number of publications in each category and their corresponding percentages of the total. The diagram revealed that the category ''Computer Science, Information Systems'' had the highest number of papers with 298 publications, followed by ''Engineering, Electric & Electronic'' with 261 publications, and ''Telecommunications'' came in third place.

3) MOST PRODUCTIVE AND TOP CITED JOURNALS

Clarifying the prolific journals publishing articles relating to blockchain and ML integration is advantageous for researchers to acquire information that will aid in making decisions about where or where not to submit manuscripts and finding journals where the research topic crosses multiple disciplines. The remaining 700 articles were published in 256 scholarly journals, and Table 6 enumerates the top 10 productive journals, their journal impact factor (JIF), and JIF quartile. The JIF is a widely used index for measuring a journal's citation impact, and data for this metric was acquired from the 2022 journal citation reports. JIF is based on the Thomson Reuters Web of Knowledge JCR Ranking 2021-2022. The JIF quartile is used to evaluate the distribution of publications for an entity (e.g., country, institution, research group, or individual) among journals from different fields [33]. According to the results provided in Table 6, EEE Access, a multidisciplinary sciences journal (i.e., that journal has more comprehensiveness in many domains), outpaced the rest of the journals by publishing the most articles (61 publications) on the research topic. Followed by, IEEE Internet Of Things Journal published 24 articles, IEEE Network published 22 publications, and IEEE Transactions On Industrial Informatics published 16 publications. The remainder of the journals are professional in some fields related to blockchain and ML-based applications. Furthermore, the majority of the journals are ranked in the first JIF quartile (Q1), which is the

TABLE 6. Top 10 productive journals publishing in the blockchain and ML-related research.

Rank	Journal	TC	TP	WoS category	JIF (Quartile)	Country
1st	IEEE ACCESS	61	1375	Computer science, Engineering, Telecommunications	3.476 (Q2)	United States
2nd	Sensors	27	246	Engineering, Instruments & Instrumentation	3.847 (Q2)	Switzerland
3rd	IEEE Internet of Things Journal	24	499	Computer science, Engineering, Telecommunications	10.238 (Q1)	United States
4th	IEEE Network	22	369	Computer science, Hardware & Architecture	10.294 (Q1)	United States
5th	Electronics	20	187	Computer science, Engineering, Physics	2.69 (Q3)	Switzerland
6th	IEEE Transactions on Industrial Informatics	16	621	Computer science, Engineering, Interdisciplinary Applications	11.648 (Q1)	United States
7th	Security & Communication Networks	15	37	Computer science, Telecommunications	1.968 (Q3)	England
8th	Transactions on Emerging Telecommunications Technologies	14	152	Telecommunications	3.31 (Q2)	England
9th	CMC-Computers Materials & Continua	14	31	Computer science, Multidisciplinary	3.86 (Q2)	United States
10th	Wireless Communications & Mobile Computing	14	28	Computer science, Engineering, Telecommunications & Methods	2.146 (Q3)	England

TABLE 7. Top 10 productive countries in blockchain and ML-related research.

Rank	Country	TP	SCP	MCP	%of publications	TC	AAC
1st	China	200	131	69	29	1876	9.38
2sd	India	100	65	35	14	584	5.84
3rd	South Korea	73	46	27	10	1345	18.42
4th	USA	44	22	22	6	587	13.34
5th	United Kingdom	30	11	19	4	420	14.00
6th	Saudi Arabia	25	13	12	4	128	5.12
7th	Canada	23	5	18	3	352	15.30
8th	Australia	21	9	12	3	516	24.57
9th	Egypt	12	6	6	2	38	3.17
10th	United Arab Emirates	11	6	5	2	357	32.45

highest-ranking quartile, and most of the cited journals have high impact factors (IF ≥ 3.4), indicating their high standing within the research community.

The papers' distribution highlighted that the research on blockchain and ML integration has been disseminated across a wide range of top-rated journals, which are centered on exploring the technology's applications in diverse fields, such as telecommunications, management, security, sustainability, and electronics. The existence of published articles in a variety of journals accentuates the interdisciplinary nature of blockchain and its flexibility to integrate with ML in multiple industries.

4) CONTRIBUTION OF LEADING COUNTRIES/INSTITUTIONS

According to the data collected, the study disclosed that scholars from over 74 nations/territories had participated in generating knowledge regarding the integration of blockchain and ML during the study period. China, as a rising power in scientific research, emerged as the dominant producer of related publications. Chinese researchers accounted for 29% of all publications, with 200 publications in the research area. India According to the data collected, the study disclosed that scholars from over 74 nations/territories had participated in generating knowledge regarding the integration of blockchain and ML during the study period. China, as a rising power in scientific research, emerged as the dominant producer of related publications. Chinese researchers accounted for 29% of all publications, with 200 publications in the research area. India is the second most prolific producer in this field, contributing 14% of the world's total publications. Korea ranked third with 73 publications. Further behind with 6 and 4% are the USA, the UK, and Saudi Arabia. Table 7 depicts the top 10 most relevant countries of blockchain and ML-related knowledge production. These findings indicated that blockchain-ML research has attracted attention from researchers worldwide. SCP indicates single-country publications, MCP indicates multiple-country publications, and AAC is the average article citations calculated using TC/TP.

Furthermore, The study's findings revealed the level of international collaboration among countries, with India and China exhibiting the highest rates of collaboration, as evidenced by their substantial number of multiple-country publications (MCP), at 69 and 35, respectively. Nonetheless, the research also indicated that international cooperation in this area is limited, as the number of single-country publications (SCP) among the top 10 most productive countries significantly surpasses their MCP count.

Figure 5 illustrates the collaboration network between countries. The lines connecting countries/regions denote their cooperative relationships, and the line thickness reflects the extent of collaboration. Notably, China emerged as the most active participant in this network, with a particularly high level of engagement with the USA, India, and Canada.

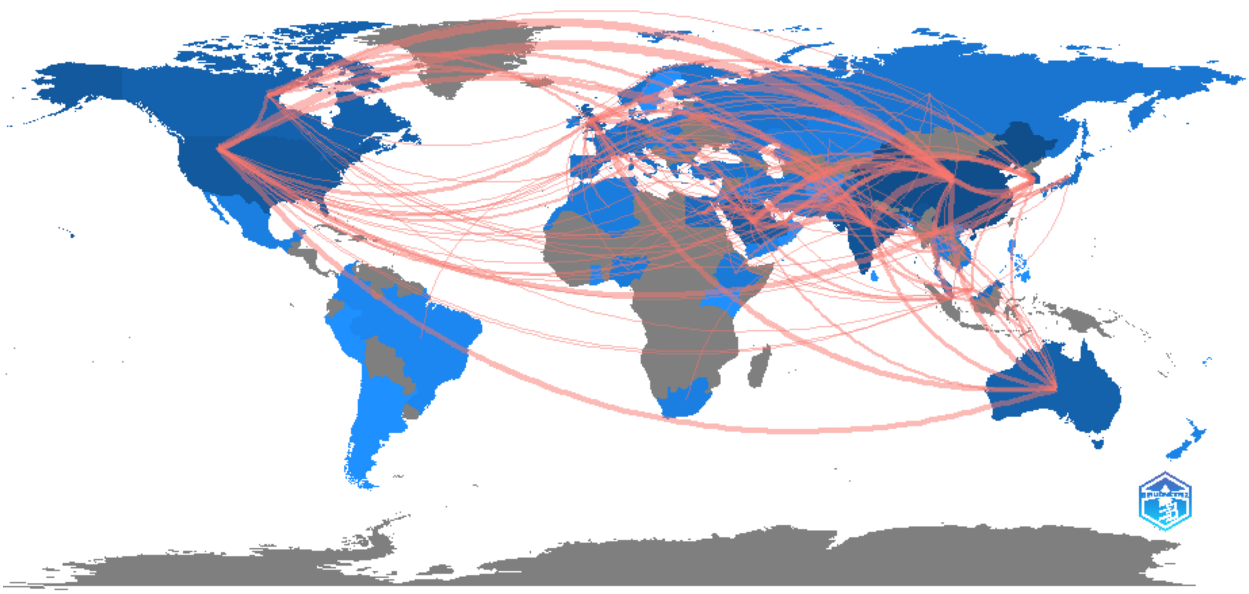

FIGURE 5. Collaboration map among countries using "Biblioshiny". Note. The countries depicted in darker shades of blue on the map indicate the countries that frequently collaborate on this research area, as evidenced by the frequency of their publications.

TABLE 8. The top 10 most productive institutions in blockchain and ML-related research.

Rank	Institution	Country	Publications
1st	King Saud University	Saudi Arabia	26
2sd	Jeju National University	South Korea	23
3rd	Huazhong University of Science and Technology (HUST)	China	17
4th	Nirma University	India	17
5th	Xidian University	China	15
6th	Asia University	Taiwan	14
7th	Nanyang Technological University	Singapore	14
8th	University of Electronic Science and Technology of China	China	14
9th	Gachon University	South Korea	12
10th	King Abdulaziz University	Saudi Arabia	12

Apart from identifying the top-performing countries, the present study also aims to recognize the most outstanding performers at the institutional level. The data emphasized the significant impact of King Saud University, which had the highest number of publications with a total of 26. Following closely, Jeju National University and Huazhong University secured the 2nd and 3rd positions with 23 and 17 total papers, respectively, indicating their substantial contributions to the field. Table 8 lists the top 10 most productive institutions. The institutions within this list are predominantly affiliated with countries/regions including China (3 institutions), Saudi Arabia (2 institutions), South Korea (2 institutions), India (1 institution), Taiwan (1 institution), and Singapore (1 institution). Alternatively, these findings reinforced the previous observation on the active involvement of these countries/regions in research related to the integration of blockchain and ML.

5) AUTHOR's INFLUENCE

In scientific fields, individuals who have significantly contributed to their area of study are regarded as prolific. These authors are crucial for research and policy formulation as they possess substantial knowledge in their domains [34]. In the realm of blockchain-ML research, Table 9 outlines statistics on the top 10 most productive authors. Out of the 2502 authors actively involved in the research of blockchain and ML convergence, S. Tanwar, JH. Park and R. Kumar have emerged as the most productive and influential authors. Among these authors, S. Tanwar has the highest number of publications to their credit (16 TP), and JH. Park has the highest h-index value (8). The most cited author in this research area is Y. Zhang, with a total of 608 citations.

6) KEYWORDS STATISTICS

This section discusses the findings of the keyword analysis in order to reveal the intellectual core and identity construction of the research discipline by looking into keywords frequently used by research papers [35]. Table 10 displays the top 10 keywords used in the paper titles. The most frequently used keywords comprised a mixture

TABLE 9. Contribution of the top 10 authors in the blockchain and ML-related research.

Rank	High-published authors		High-cited authors		h-index	
	Author	Count	Author	Freq.	Author	h-index
1st	S. Tanwar	16	Y. Zhang	608	JH. Park	8
2nd	JH. Park	13	YY. Dai	441	R. Kumar	8
3rd	R. Kumar	13	S. Maharjan	441	YC. Byun	8
4th	YC. Byun	12	V. Chamola	370	S. Tanwar	7
5th	P. Kumar	11	M. Guizani	368	P. Kumar	7
6th	GP. Gupta	10	V. Hassija	356	GP. Gupta	7
7th	R. Tripathi	10	V. Gupta	353	R. Tripathi	7
8th	N. Kumar	10	S. Tanwar	340	N. Kumar	7
9th	Z. Shahbazi	10	JH. Park	336	G. Srivastava	6
10th	R. Gupta	10	K. Salah	300	Z. Shahbazi	6

TABLE 10. Top 10 frequent keywords in the blockchain and ML-related publications.

Rank	Author keywords (DE)	No. of articles	Keywords plus (ID)	No. of articles
1st	Blockchain	456	Internet	121
2nd	Machine Learning	154	Challenges	74
3rd	Artificial Intelligence	114	Framework	57
4th	Security	100	Management	48
5th	Deep Learning	96	Things	44
6th	Internet of Things	82	Blockchain	43
7th	Smart Contract	52	Security	42
8th	Federated Learning	51	IoT	41
9th	Privacy	46	System	40
10th	Data Models	38	Networks	36

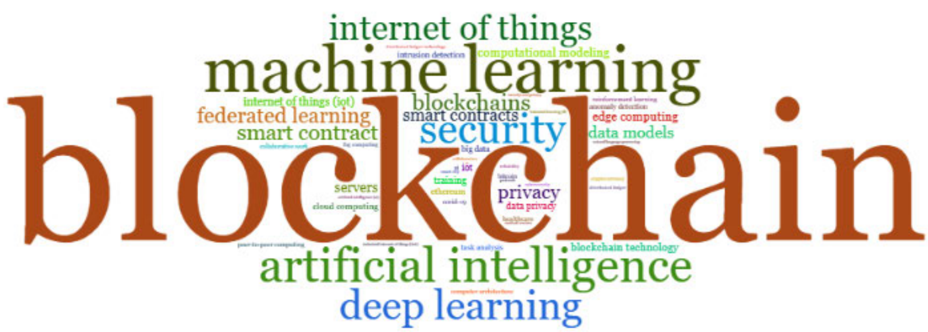

FIGURE 6. Word cloud of author keywords.

of Blockchain, machine learning, Internet of Things, and security.

The WoS offers researchers two types of keywords, namely author keywords and keywords plus. Author keywords are a reflection of the author's standpoint and provide a concise summary of the primary themes explored in their article. On the other hand, keywords plus are generated using an algorithm that assesses the frequency of words and phrases found in the title and references of the publication. Figures 6 and 7 illustrate a word cloud depicting the top 50 author keywords and keywords plus. The size of each word reflects its frequency of occurrence. As shown in Figure 6, the central position is occupied by the keyword "blockchain," followed by "machine learning" and "artificial intelligence," which are the most common author keywords. On the other hand, the results in Figure 7 revealed that the most frequently used keywords plus are "internet," "challenges," and "blockchain,", indicating a broader range of topics than author keywords.

C. SCIENCE MAPPING

In the context of research, science mapping concerns the relationships between research elements and their structural associations. The current investigation endeavors to accomplish its objectives through the utilization of several techniques, such as citation analysis, co-citation analysis, co-authorship analysis, and keyword co-occurrence analysis. By incorporating network analysis with these methodologies, it becomes possible to effectively demonstrate both the bibliometric structure and intellectual framework of the research area [36].

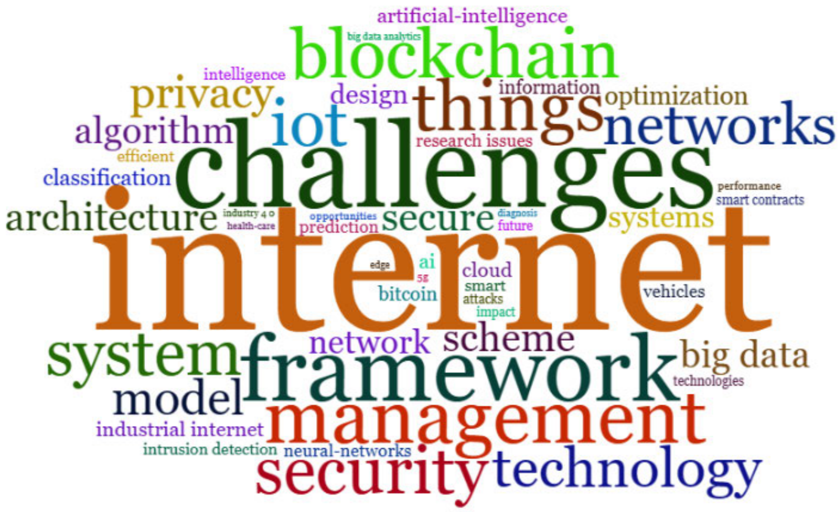

FIGURE 7. Word cloud of keyword plus.

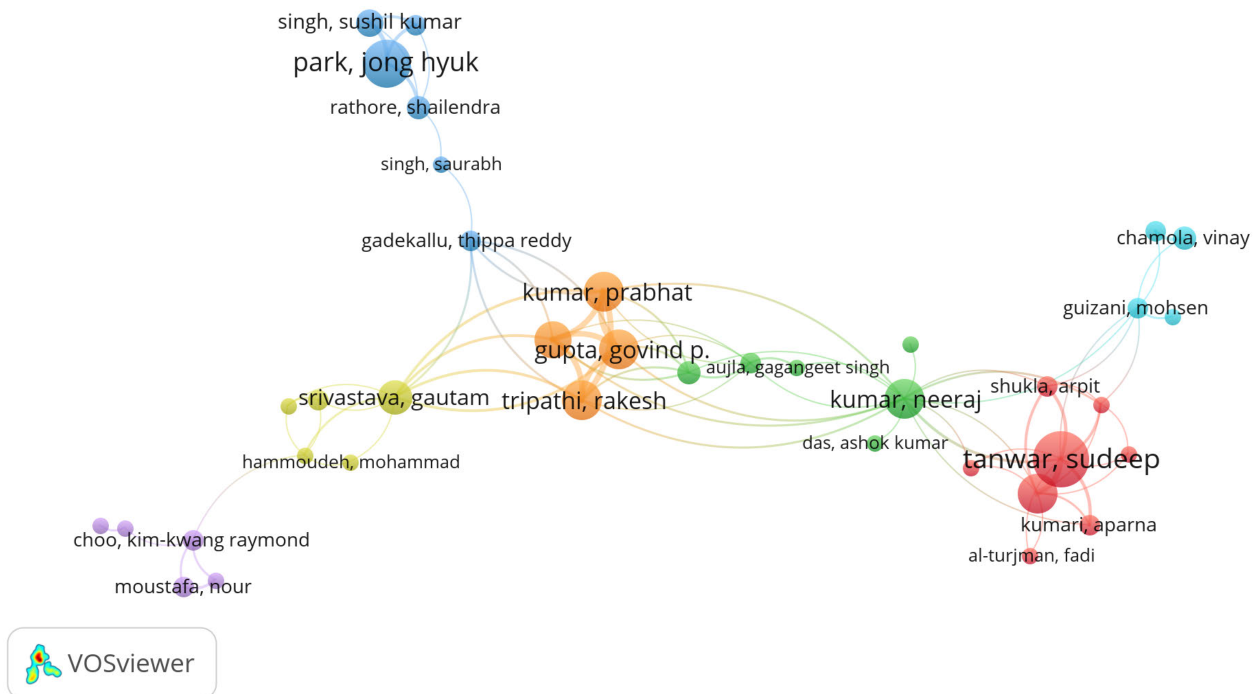

FIGURE 8. Collaborative network of co-authors in the field of blockchain and ML integration.

1) COLLABORATIVE CO-AUTHORS NETWORK ANALYSIS

A useful approach in cooperative network analysis is the core author method, which can assist researchers in understanding the dynamics and updates of critical authors within a research field. Using the VOSviewer tool, authors can be categorized into various clusters and represented by different colors based on their collaboration patterns. To generate a simplified co-authorship collaboration network, 38 authors were selected with the highest total link strength, considering only authors who had published at least three documents. The generated network is displayed in Figure 8, where the size of each circle indicates the frequency of co-author publications; larger circles represent more publications. The lines connecting two authors represent a collaborative relationship. Based on the bibliometric analysis, seven distinct clusters were identified. Furthermore, our analysis revealed that Tanwar played a prominent role in co-authorship within the blockchain and ML convergence areas. It is noteworthy that authors within the same color cluster have a strong cooperative relationship.

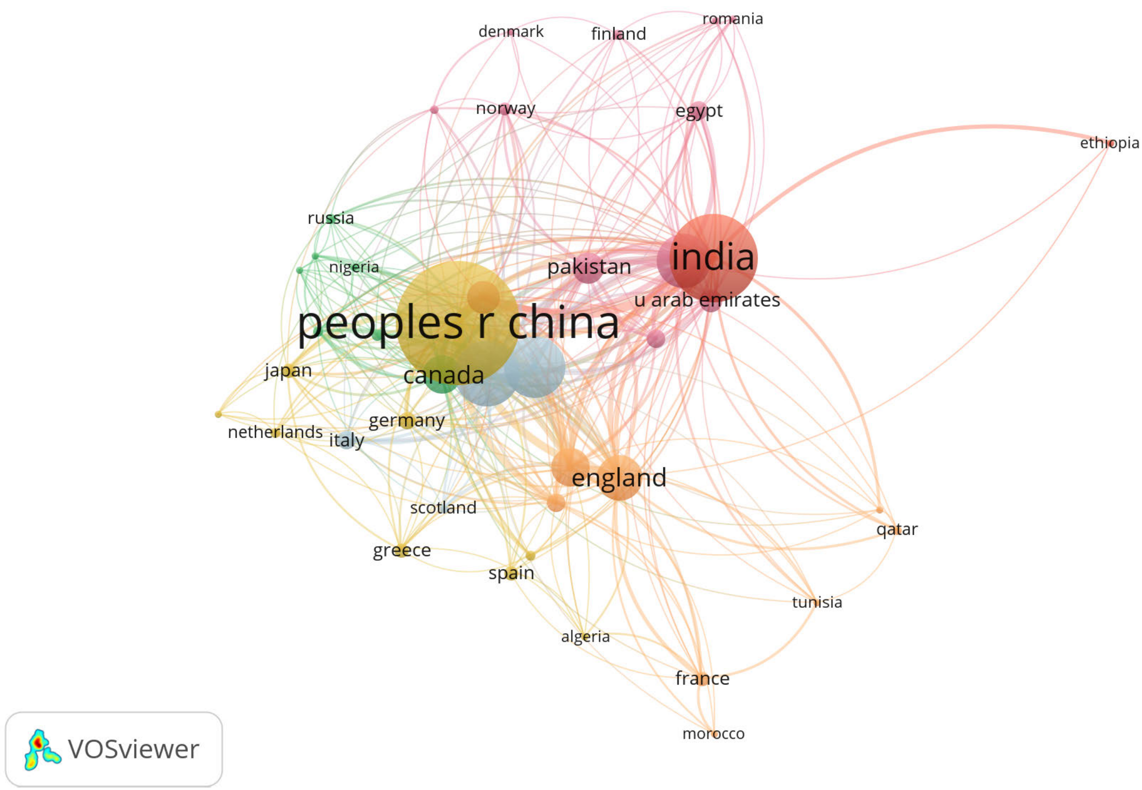

FIGURE 9. The country co-authorship network of blockchain and ML integration research field.

2) COLLABORATIVE COUNTRIES NETWORK ANALYSIS

An essential type of co-authorship analysis is country co-authorship analysis, which can reveal the level of interaction between countries and influential countries in a particular field. By utilizing VOSviewer software, a country co-authorship network was generated for blockchain and ML-related publications, which is illustrated in Figure 9. The map uses various colors to represent the diversification of research directions, and the size of each node reflects the number of publications from a specific country/region. Moreover, the thickness of the lines connecting two countries/regions demonstrates the strength of their collaborative relationship, with thicker lines indicating stronger collaboration. Table 11 presents the top 10 countries that have collaborated the most in the blockchain-ML research field, which is consistent with the information in Figure 9. Notably, China has been the most productive country, with 228 publications, and has established the strongest collaborative ties with other countries over the last few decades.

TABLE 11. The top 10 collaborative countries/regions.

Rank	Country	Publications	Citations	Total Link Strength
1st	China	228	2685	188
2sd	India	147	1671	154
3rd	USA	97	1892	140
4th	South Korea	90	1474	93
5th	Saudi Arabia	77	569	133
6th	England	61	1115	109
7th	Australia	49	984	95
8th	Canada	47	712	88
9th	Taiwan	38	730	81
10th	Pakistan	36	529	78

3) COLLABORATIVE INSTITUTIONS NETWORK ANALYSIS

To examine collaborative institutions within the research domain, an institute co-authorship network was constructed through VOSviewer. The dataset included 1210 institutions, from which 55 key organizations were identified using a threshold requirement of at least 5 documents per organization. Figure 10 depicts the generated network; each node represents a distinct institution, color-coded to differentiate between them, while the lines indicate the level of collaboration between institutions. The findings suggested that Asia University and Nirma University exhibit the strongest collaborative relationships and that institutions within the same country display a higher tendency to collaborate, potentially due to improved communication.

4) REFERENCE CITATION ANALYSIS

In order to understand the structure of the citation network within blockchain-ML research, the VOSviewer software was utilized to analyze the reference relationships among each publication. Using a minimum threshold of 10 citations per document, a citation network of 214 documents was

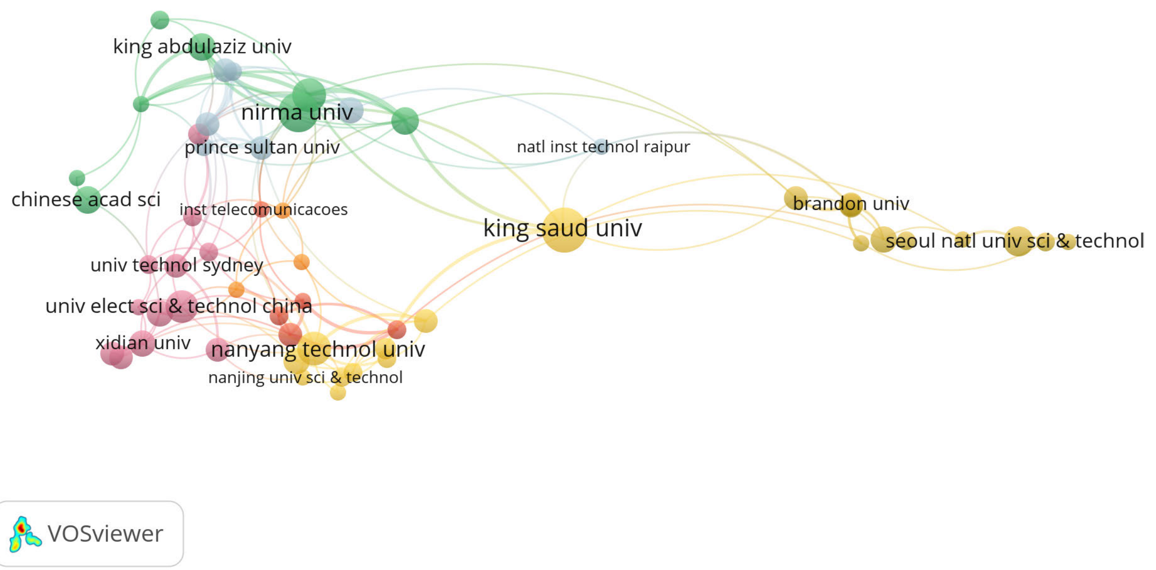

FIGURE 10. The institutions' co-authorship network of blockchain and ML integration research field.

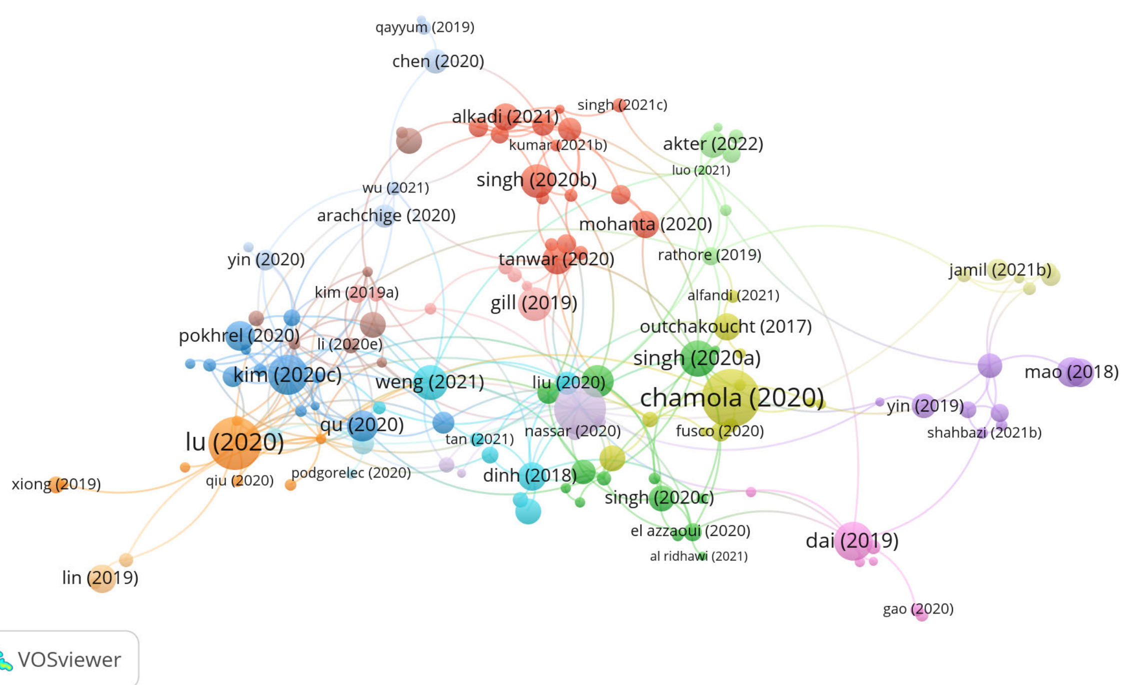

FIGURE 11. The citation network of cited references.

identified, consisting of 134 nodes and 293 links, as illustrated in Figure 11. The most frequently cited paper in the network is Chamola (2020), a journal article published in IEEE Access entitled "A Comprehensive Review of the COVID-19 Pandemic and the Role of IoT, Drones, AI, Blockchain, and 5G in Managing its Impact," with 353 citations, followed by Lu with 285 citations. It is important to note that some highly cited papers were not included in Figure 11 due to the parameters set during network generation. Thus, Table 12 presents the top 20 most highly cited research articles that have contributed to the field of research, with total citations per year providing a measure of their overall impact regardless of publication year.

Citation burst detection is a valuable analytical method that demonstrates the evolving trends of references in a research area over time, indicating a surge of knowledge that has captured the attention of researchers [57]. In order to trace the evolution of popular research topics and stimulate

TABLE 12. Highly cited research papers on blockchain and ML convergence.

Rank	Publication	Title	Journal	TC	TC per Year
1st	[37]	A Comprehensive Review of the COVID-19 Pandemic and the Role of IoT, Drones, AI, Blockchain, and 5G in Managing its Impact	IEEE ACCESS	353	117.67
2nd	[38]	Blockchain and Federated Learning for Privacy-Preserved Data Sharing in Industrial IoT	IEEE Transactions on Industrial Informatics	285	95
3rd	[39]	Blockchain for AI: Review and Open Research Challenges	IEEE ACCESS	273	68.25
4th	[40]	Blockchained On-Device Federated Learning	IEEE Communications Letters	170	56.67
5th	[41]	Blockchain and Deep Reinforcement Learning Empowered Intelligent 5G Beyond	IEEE NETWORK	156	39
6th	[42]	BlockIoTIntelligence: A Blockchain-enabled Intelligent IoT Architecture with Artificial Intelligence	Future Generation Computer Systems	132	44
7th	[43]	DeepChain: Auditable and Privacy-Preserving Deep Learning with Blockchain-Based Incentive	IEEE Transactions on Dependable and Secure Computing	127	63.50
8th	[44]	Convergence of blockchain and artificial intelligence in IoT network for the sustainable smart city	Sustainable Cities and Society	121	40.33
9th	[45]	Transformative effects of IoT, Blockchain and Artificial Intelligence on cloud computing: Evolution, vision, trends and open challenges	Internet of Things	115	28.75
10th	[46]	DeepCoin: A Novel Deep Learning and Blockchain-Based Energy Exchange Framework for Smart Grids	IEEE Transactions on Engineering Management	105	35
11th	[47]	Decentralized Privacy Using Blockchain-Enabled Federated Learning in Fog Computing	IEEE Internet of Things Journal	99	33
12th	[48]	Credit Evaluation System Based on Blockchain for Multiple Stakeholders in the Food Supply Chain	International Journal of Environmental Research and Public Health	96	19.20
13th	[49]	Federated Learning With Blockchain for Autonomous Vehicles: Analysis and Design Challenges	IEEE Transactions on Communications	95	31.67
14th	[50]	Machine Learning Adoption in Blockchain-Based Smart Applications: The Challenges, and a Way Forward	IEEE ACCESS	92	30.67
15th	[51]	Swarm Learning for decentralized and confidential clinical machine learning	NATURE	88	44
16th	[52]	An intelligent blockchain-based system for safe vaccine supply and supervision	International Journal of Information Management	87	29
17th	[53]	AI and Blockchain: A Disruptive Integration	COMPUTER	86	17.20
18th	[54]	Making Knowledge Tradable in Edge-AI Enabled IoT: A Consortium Blockchain-Based Efficient and Incentive Approach	IEEE Transactions on Industrial Informatics	86	21.50
19th	[55]	An intelligent Edge-IoT platform for monitoring livestock and crops in a dairy farming scenario	Ad Hoc Networks	79	26.33
20th	[56]	Survey on IoT security: Challenges and solution using machine learning, artificial intelligence and blockchain technology	Internet of Things	77	25.67

future investigations, Figure 12 presents the top 10 references with the strongest citation bursts between 2017 and 2022, as identified by CiteSpace (using the parameters: year(s) per slice: 1; node type: reference; pruning: pathfinder; g-index: 25). In this visualization, the blue line indicates the complete period, whereas the red line represents the duration of the citation burst for each reference. Generally, the more attention a reference receives during a specific period, the longer the burst duration and the higher the burst intensity. Figure 12 displays the reference with the highest citation burst strength (3.11), originating from Nakamoto's white paper that introduced the peer-to-peer electronic payment model ''bitcoin'' in 2018 [2], which is considered the pioneering work that laid the groundwork for blockchain technology. In Fernandez's publication, there is evidence of a notable citation surge (2.97) that took place between 2019 and 2020. This surge is primarily due to his examination of the potential impact of blockchain technology on conventional cloud-based IoT applications. Specifically, Fernandez analyzes the ways in which blockchain can be customized to address the unique requirements of IoT, leading to the development of Blockchain-based IoT (BIoT) applications. In his work, Fernandez also delves into the challenges that come with designing, developing, and deploying BIoT applications, as well as possible solutions for optimization [58].

5) THE JOURNALS CO-CITATION ANALYSIS

Figure 13 plots a network of co-citations among journals, which serves to categorize them according to disparate topics and ascertain the most influential journals in each category. Out of 211 journals meeting the minimum citation threshold of 20, those with the most significant implications for the research field are listed. The three journals with the highest number of citations are IEEE Access (1461 citations), IEEE Internet of Things (996 citations), and IEEE Transactions on Industrial Informatics (564 citations). Interestingly, these top three journals belong to different categories, as indicated by the color-coding in Figure 13, suggesting that they focus on distinct research directions. Novice researchers can benefit from the information presented in Figure 13, which reflects the quality of journals' publications and can aid in identifying the distribution of high-quality journals in this field.

Top 10 References with the Strongest Citation Bursts

References	Year	Strength	Begin	End	2017 - 2022
Nakamoto S., 2008, BITCOIN PEER TO PEER, V0, P9	2008	3.11	**2018**	2020	
Fernandez-Carames TM, 2018, IEEE ACCESS, V6, P32979, DOI 10.1109/ACCESS.2018.2842685, DOI	2018	2.97	**2019**	2020	
Dorri A, 2017, IEEE COMMUN MAG, V55, P119, DOI 10.1109/MCOM.2017.1700879, DOI	2017	2.54	**2019**	2020	
Christidis K, 2016, IEEE ACCESS, V4, P2292, DOI 10.1109/ACCESS.2016.2566339, DOI	2016	2.07	**2019**	2020	
Khan MA, 2018, FUTURE GENER COMP SY, V82, P395, DOI 10.1016/j.future.2017.11.022, DOI	2018	1.88	**2019**	2020	
Androulaki E, 2018, EUROSYS 18 ...... NTH EUROSYS CONFERENCE, V0, P0, DOI	2018	1.37	**2019**	2020	
LAMPORT L, 1982, ACM T PROGR LANG SYS, V4, P382, DOI 10.1145/357172.357176, DOI	1982	1.03	**2019**	2020	
Sikorski JJ, 2017, APPL ENERG, V195, P234, DOI 10.1016/j.apenergy.2017.03.039, DOI	2017	1.03	**2019**	2020	
Lu YL, 2020, IEEE T IND INFORM, V16, P4177, DOI 10.1109/TII.2019.2942190, DOI	2020	1.09	**2020**	2022	
Liu CH, 2019, IEEE T IND INFORM, V15, P3516, DOI 10.1109/TII.2018.2890203, DOI	2019	0.91	**2020**	2022	

FIGURE 12. Top 10 references with the highest citation bursts.

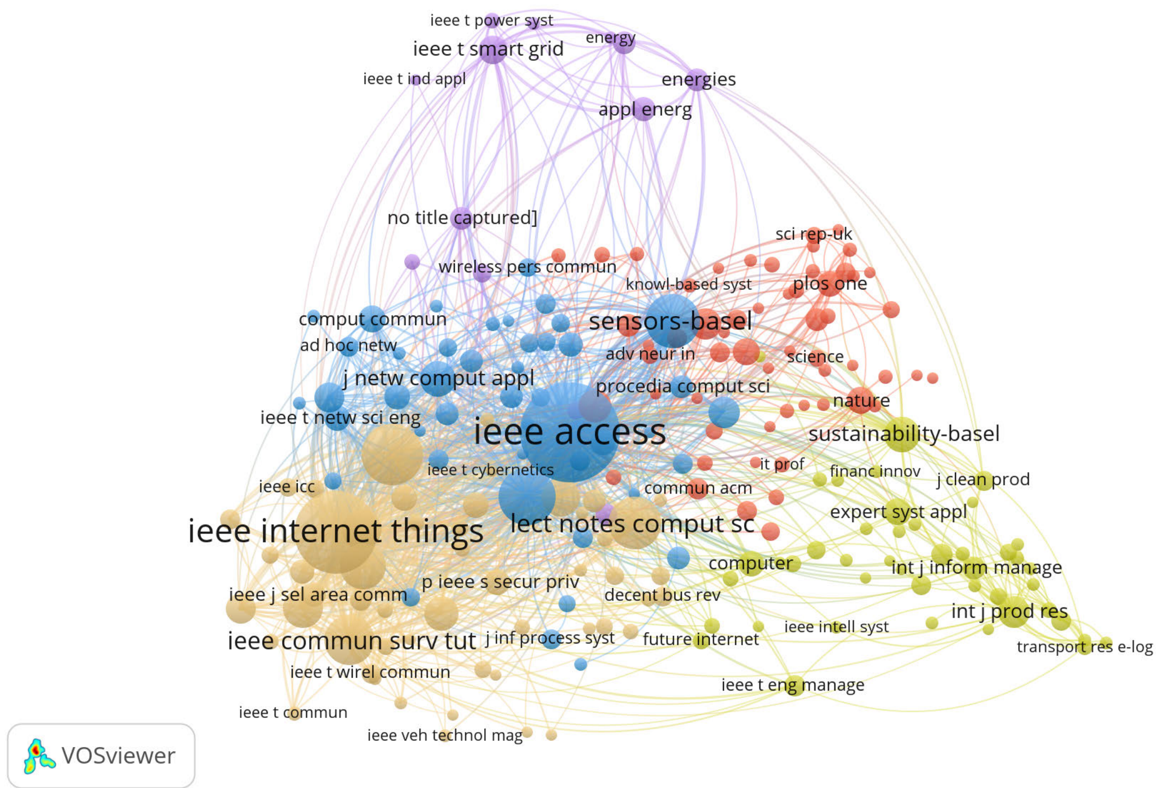

FIGURE 13. Journal co-citation network for publications on the integration of blockchain and ML.

D. RESEARCH HOTSPOTS: KEYWORD CO-OCCURRENCE NETWORK ANALYSIS

A useful approach to scrutinizing the contents of a corpus of articles is keyword co-occurrence analysis, which examines the frequency of specific keywords to uncover prevailing research topics and monitor changes in the boundaries of a scientific knowledge domain. The fundamental idea behind this method is that if particular keywords frequently occur together in articles, it indicates that the corresponding concepts are closely associated, implying thematic proximity within the field. In this research, we utilized VOSViewer's co-occurrence analysis to produce a visual representation of author keywords. To account for variations in pluralization and word forms, occurrences of keywords with similar meanings (e.g., blockchain and blockchains) were consolidated.

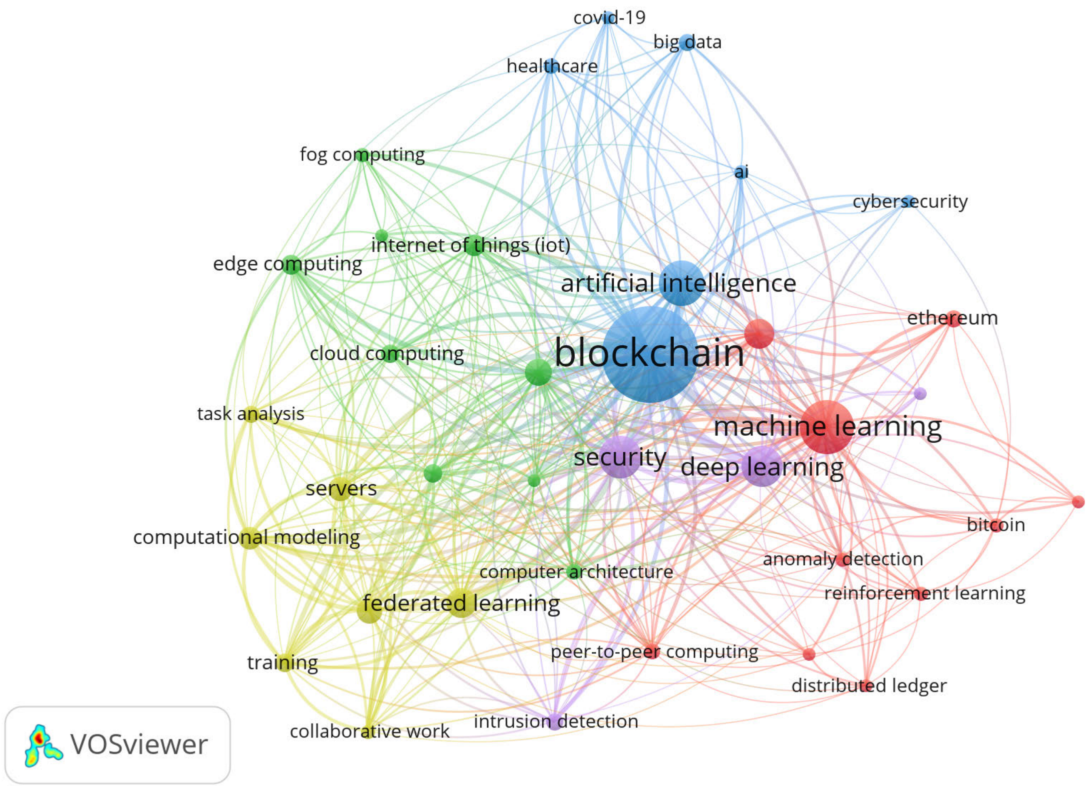

FIGURE 14. Keyword co-occurrence Network visualization.

To make the visualization more manageable, a minimum keyword occurrence of 10 was set, resulting in 43 out of 1714 extracted keywords throughout the review corpus meeting the frequency threshold and being included in the visualization (Figure 14). The final keyword co-occurrence network highlighted the domains of blockchain and ML research, with 43 nodes and 533 relations and an average of 12.3 relations between keywords. The VOSviewer software used the smart local moving algorithm to generate four significant clusters representing four major research themes, with each node in Figure 14 representing a keyword, and the size and thickness of the node and link representing the occurrence frequency and co-occurrence of the keyword, respectively. The blue cluster, located at the center, encompasses the most commonly used concepts that have garnered significant focus from scholars. Additionally, a keyword heat map was created based on 43 keywords related to the topic area. Figure 15 shows the heat map, with darker colors indicating higher frequencies of keywords and therefore more research activity in the area. Among the author keywords depicted in Figure 15, artificial intelligence, blockchain, machine learning, security, and smart contracts emerged as the most prominent and extensively discussed keywords in the highly integrated network. This underscores their relative significance in the field.

Table 13 displays the most frequent keywords in each cluster, as determined through cluster analysis. The main theme derived from the keywords was used to assign a label to each cluster in the network. The subsequent sub-sections offer a narrative review of several essential themes and trends encompassed in each cluster. It should be emphasized that these summaries are merely illustrative and do not cover all aspects.

1) BLOCKCHAIN-BASED ML APPLICATIONS

The blue cluster surrounds the topics of AI, big data, cybersecurity, healthcare, and COVID-19. Among the various data-driven technologies, both blockchain and ML offer great potential and there is a growing interest in integrating them for clinical data management and analysis within healthcare. Blockchain has been suggested as a secure means of storing healthcare-related data to facilitate sharing, exchanging, and analyzing it between various providers [59]. It can also act as a digital backbone to interface with other AI technologies, including ML, to ensure data security and transparency. By utilizing the strong data storage capabilities of blockchain in an encrypted, distributed ledger format and the predictive capabilities of ML, informed decisions can be made [60]. Kumar et al. [61] proposed a blockchain-based federated learning framework that enables collaborative learning from accurate data collected through multiple hospitals using different types of computed tomography (CT) scanners to identify COVID-19 patterns in lung CT scans. The data is shared among hospitals through a

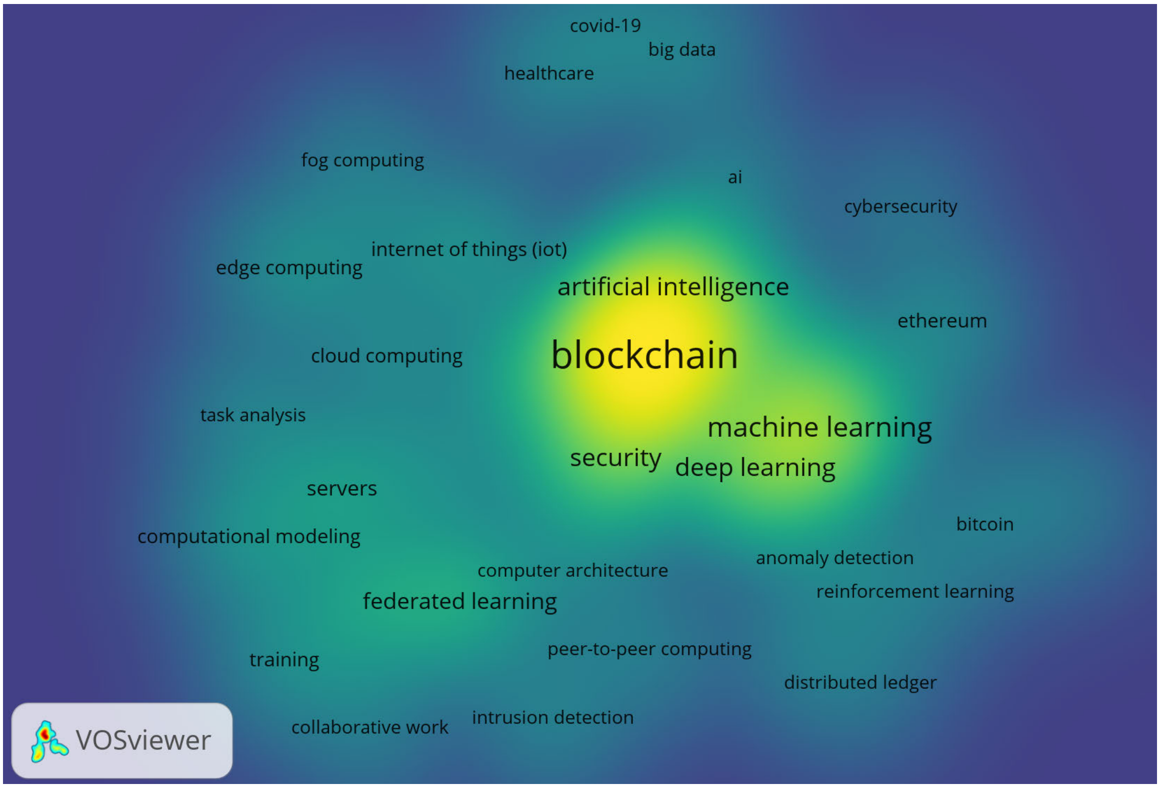

FIGURE 15. Keyword co-occurrence Density visualization.

TABLE 13. The most occurring keywords within the cluster, ranked by frequency.

Clusters	Cluster #1 (Blue)	Cluster #2 (Red)	Cluster #3 (Yellow)	Cluster #4 (Green)
Theme	Blockchain-based ML Applications	Blockchain Technical Aspects	ML application for blockchain ecosystem	Blockchain Priacy and Security
Keywords	Blockchain, IoT, AI, Artificial Intelligence, Deep Learning, Big Data, Covid-19, Healthcare, Cybersecurity, Smart City	Machine Learning, Smart Contract, Cryptocurrency, Peer-to-peer Computing, Ethereum, Anomaly Detection, Distributed Ledger, Bitcoin	Federated Learning, Task Analysis, Servers, Computational Modeling, Data Models, Training Data, Collaborative Work, Intrusion Detection	Security, Data Privacy, Cloud Computing, Computer Architecture, Edge Computing, Fog Computing, Reliability

decentralized ledger over the public network while preserving privacy.

Conversely, with the evolution of cybersecurity measures and new regulations, there is potential for improved data protection. The swift progress of blockchain and AI technology has created novel prospects for sharing and amalgamating data in ways that were previously unexplored. These advancements offer the possibility of better cybersecurity practices and a more ethical approach to handling personal data [62]. Blockchain and distributed ledger technologies provide an innovative way to protect user data by utilizing decentralized identity and other privacy mechanisms. Moreover, AI technology can enhance blockchain-based privacy solutions by allowing users to handle their data more effectively while assuring the accuracy, fairness, and reliability of data and models derived from it. Reference [61] proposed an intelligent cybersecurity platform aimed at helping small and medium-sized enterprises (SMEs) secure their systems and networks. This platform employs proactive security techniques, ML, and blockchain to provide various micro-services, such as detecting DDoS, SQLi, and DGA attacks. The proposed platform aids SMEs in prevention, detection, containment, and response, reducing the potential impact of an attack and promoting the quick restoration of systems to their normal state.

2) BLOCKCHAIN TECHNICAL ASPECTS

The red cluster entails the documents related to integrated applications of ML and blockchain that can enhance the processes in the finance industry through cryptocurrencies such as Bitcoin and Ethereum, wherein the concepts of machine learning, smart contracts, cryptocurrency, Ethereum, Bitcoin, and distributed ledger appear prominently. Blockchain, known for maintaining secure and decentralized ledger transactions across a peer-to-peer network, is the fundamental

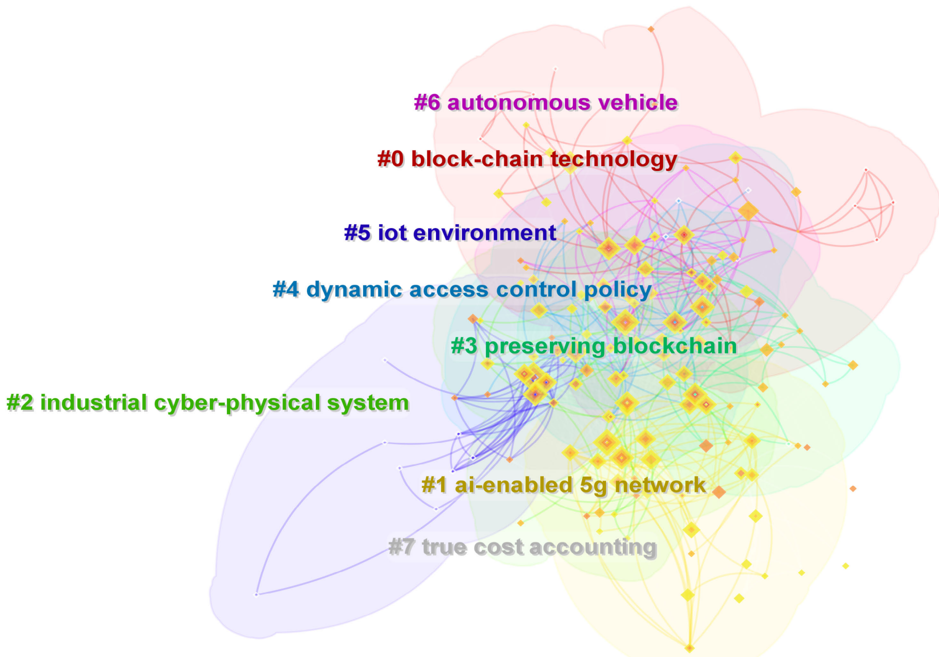

FIGURE 16. Keywords clustering map visualization.

technology underlying emerging cryptocurrencies, including Bitcoin [63]. Bitcoin, the cornerstone of the modern digital cryptocurrency system, was one of the first implementations of blockchain technology and has attracted a lot of attention. Along with Ethereum, a blockchain platform that focuses on smart contracts, these two technologies form the core of modern cryptocurrency development. In terms of smart contracts, Ethereum [64] was a pioneering platform, having introduced the concept of automated protocols that can facilitate, verify, and enforce negotiations and agreements among multiple untrustworthy parties.

Over the past few years, the rapid growth and increasing popularity of Bitcoin and other cryptocurrencies have triggered a significant surge in blockchain research and its various applications. The future direction of this trend includes exploring ways to prevent illegal activities such as robbery and ransomware by de-anonymizing entities in the context of cryptocurrencies. To this end, [65] introduced a new approach to de-anonymizing Bitcoin Blockchain transactions, which utilizes Supervised ML to predict the types of yet-unidentified entities. This approach aims to identify high-risk counterparties and potential cybercriminal activities. Additionally, the extent of Bitcoin's anonymity is investigated by clustering, identifying, and categorizing Bitcoin addresses, which sheds light on the possibility of revealing the identity of users or organizations in the Bitcoin ecosystem. Reference [66] suggests utilizing multiple ML models for the identification of anomalous transactions in different digital currency markets. On the other hand, [67] aimed to develop a deep learning model based on a multiplicative long short-term memory (LSTM) architecture and an attention mechanism that incorporates technical indicators to enhance the accuracy and reduce the error rate of bitcoin price prediction.

3) ML APPLICATION FOR BLOCKCHAIN ECOSYSTEM

The potential of ML for improving blockchain-based applications lies in its ability to analyze and predict data, optimize data-sharing routes, and enhance consensus-building. The decentralized nature of blockchain also presents an opportunity to build more accurate ML models that minimize errors such as duplication, missing data, errors, and noise. By prioritizing data, blockchain can eliminate data-related issues in ML models. Custom models can be created for specific segments of the blockchain to detect fraud and intrusion. For example, [68] developed an intelligent intrusion detection system (IDS) that leverages blockchain technology to detect and avert cyberattacks in IoT environments. By using smart contracts to regulate interactions among agents, this system can be distributed to remote hosts while maintaining secure communication.

4) BLOCKCHAIN PRIVACY AND SECURITY

The last cluster examines blockchain security and data privacy. Blockchain is designed to handle security breaches such as data tampering, alterations, distributed denial-of-service attacks, and double-spending. However, it requires additional measures to secure data and maintain privacy in distributed storage and data sharing [75]. As privacy and security are crucial requirements for big data, AI, data privacy, privacy-preserving techniques, security, and smart contracts are necessary to gain user confidence and loyalty. To address

TABLE 14. Key clusters within the blockchain and ML-related research.

Cluster	Label (LLR)	Size	Silhouette	Average Year	Top Terms	Major citing article
#0	Block-chain technology	29	0.626	2019	deep learning, smart contract, neural network	[69]
#1	AI-Enabled 5g network	23	0.717	2020	challenge, management, security	[70]
#2	Industrial cyber-physical system	22	0.588	2021	iot, blockchain technology, secure	[71]
#3	Preserving blockchain	21	0.631	2020	system, intrusion detection, anomaly detection	[61]
#4	Dynamic access control policy	19	0.752	2019	ML, big data, blockchain	[72]
#5	IoT environment	19	0.858	2019	artificial intelligence, internet, internet of thing	[45]
#6	Autonomous vehicle	19	0.732	2020	network, data model, federated learning	[73]
#7	True cost accounting	8	0.872	2021	impact, information, opportunity	[74]

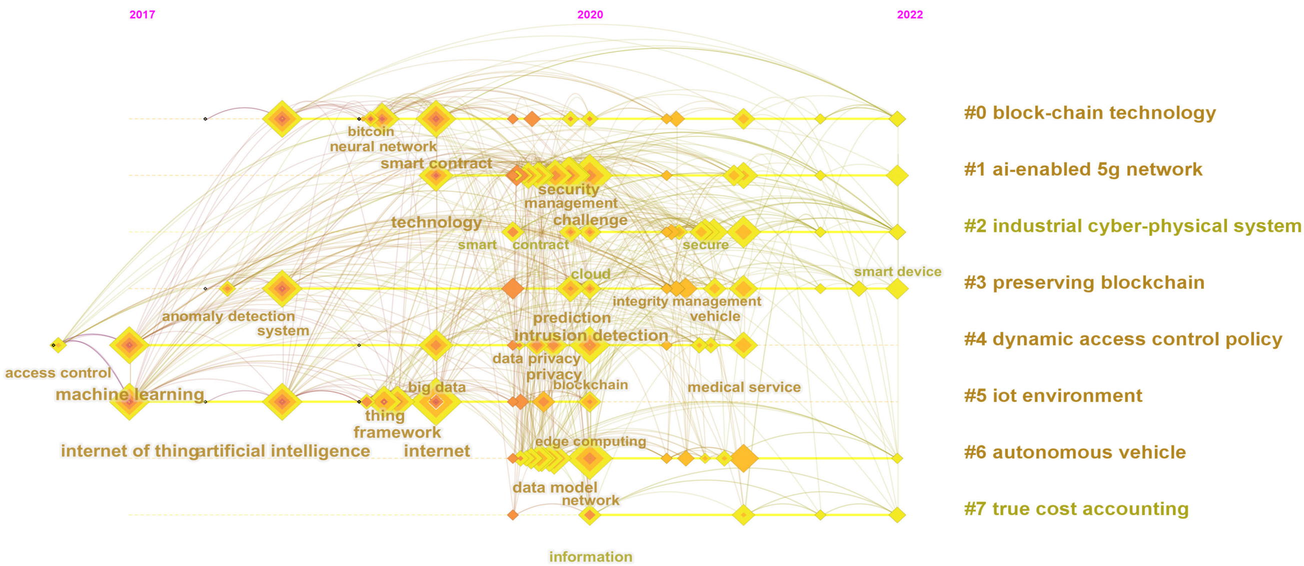

FIGURE 17. Timeline view visualization of keywords clusters.

the aforementioned security and data privacy issues that remain a critical challenge in blockchain technology. Reference [76] introduced TrafficChain, a decentralized system for collecting traffic information that ensures privacy and security while leveraging fog/edge computing infrastructure. The system's effectiveness was enhanced by implementing a two-tiered blockchain structure, while user privacy and travel patterns were safeguarded with a privacy-preserving technique implemented by the authors. Moreover, the authors integrated long short-term memory (LSTM)-based deep learning methods to counter potential Byzantine and Sybil attacks. Likewise, [77] research provided a novel approach to address quality of service (QoS) concerns regarding security, authenticity, and reliability of transmitting patient health data (PHD) among healthcare IoT devices, fog nodes, wearable device users, physicians, and cloud servers by utilizing a fog computing (FC)-based blockchain approach.

E. EMERGING RESEARCH TRENDS: KEYWORD CLUSTERING ANALYSIS

The inadequate strength of hotspots in reflecting research trends for a particular academic area is due to the oversight of the impact that varying literature timelines can have. In order to address this limitation, this study utilized CiteSpace to perform cluster analysis, which enabled the creation of a knowledge map displaying the clustering of keywords related to research on the integration of blockchain and ML. Furthermore, analyzing the co-citation clustering results over the entire time frame can be beneficial in conducting a thorough investigation of the knowledge field's evolution through a time-series analysis. To delve deeper into the findings, the study focused on the largest clusters, as depicted in Figure 16. This approach enabled a more thorough analysis of the selected clusters.

Keyword co-citation clusters are generated employing CiteSpace for the chosen node type of "keyword" and specific parameter settings (year(s) per slice: 1; pruning: pathfinder and pruning the merged work; g-index: k=15). These clusters are then labeled using the log-likelihood ratio (LLR) weighting algorithm in CiteSpace. Figure 17 depicts a high-frequency keyword clustering visualization. On the other hand, Table 14 presents the labeling patterns of the clusters, which were derived using a log-likelihood ratio (LLR) weighting algorithm. The algorithm seeks to ensure that the labels of the clusters are both unique and comprehensive. It is worth noting that there may be some overlap between the clusters. The silhouette is used to assess the level of cluster homogeneity or consistency. A score greater than 0.7 indicates that the clustering results are trustworthy and convincing. Top terms reveal the mainstream research focuses of each cluster. The clustering analysis yielded high-quality and rational results, as evidenced by the weighted mean silhouette score ($S = 0.7788 \geq 0.7$) and modularity ($Q = 0.3824 \leq 0.3$).

CiteSpace offers a timeline visualization map of keyword co-citation clusters, allowing for a more intuitive and user-friendly approach to depict the historical evolution and temporal distribution of knowledge domains. This approach underlines the connections between clusters as well as the temporal span of articles within each cluster [78]. It is particularly useful in identifying emerging trends and monitoring their dynamic evolution over time. CiteSpace software was used to produce a timeline visualization knowledge map of the research field, as illustrated in Figure 17. Each cluster axis depicts keyword nodes and node-link information associated with a specific time period, revealing the time distribution and precedence relationships among clusters. Nodes are positioned based on the year of the first appearance of the keyword within a cluster, and the keywords are spread out according to their respective years of occurrence, thereby illustrating the evolutionary trend in each cluster.

In terms of the time dimension, the clustering axis reveals that the cluster related to "dynamic access control policy" (#4) and "IoT environment" (#5) emerged early in the research area. However, the bulk of the associated keywords broke out after 2019. On the other hand, the cluster associated with "true cost accounting" (#7) has the latest start time, and its research content continues to expand. The current popular research topics in the field of blockchain-ML are "blockchain technology," "AI-enabled 5G network," "industrial cyber-physical system," "preserving blockchain," and "autonomous vehicle." With the rapid development of technology, numerous research studies are expected to emerge shortly. Therefore, summarizing research outcomes becomes crucial, which emphasizes the significance of this paper.

V. CONCLUSION

Blockchain and ML are promising technologies with vast potential for future applications. Despite their inherent differences, the prospect of integrating these two technologies has garnered attention from experts and scholars. However, there has been a shortage of research consolidating and examining the latter insights on the combined use of blockchain and ML applications. This bibliometric review aims to fill this knowledge gap by providing a thorough and up-to-date overview of the field as well as identifying the intellectual framework within it.

The study provides new evidence in the literature by using Bibliometrix, CiteSpace, and VOSviewer visualization software to conduct a thorough analysis of the performance and scholarly productivity in the area of blockchain and ML integration, answering the research questions outlined in Section I. Based on the PRISMA methodology and a specific set of criteria for inclusion, a total of 700 articles published in peer-reviewed journals from 2017 to 2022 are retrieved from the WOS Core Collection database and subsequently included in the analysis. The study identifies the basic status of research, including posting trends, the most productive journals, institutions, category distribution, and countries based on highly cited articles. The paper also employs various bibliometric methods, such as collaborative network analysis, co-citation analysis, and co-occurrence analysis, to map out the scientific knowledge maps and the evolution of research hot topics and knowledge bases.

The findings have revealed that there was limited research activity in this area before 2017, but there has been an increase in interest since then. Furthermore, the study has identified the top academic outlets that published blockchain-ML integration research. Among these outlets, IEEE ACCESS, Sensors, IEEE Internet of Things Journal, and IEEE Network are found to be the most influential, although relevant articles are also found in other top-tier journals such as IEEE Transactions on Industrial Informatics, Sustainable Cities & Society, and IEEE Transactions on Intelligent Transportation. The study has further explored the contributions of different countries to this field, and it is found that both developed countries like the USA and South Korea as well as emerging economies such as China and India have devoted significant attention to this research area. While early contributions are primarily from Western Asian academic institutions, there has been a noticeable shift in research efforts toward East Asia. In addition, the study has identified the most influential articles in this field, which could serve as a foundation for individuals seeking to understand the research area better. Co-citation analysis is used to identify recent publications that have the potential to make significant contributions to the field and spark further research. The study employs VOSviewer to identify research hotspots by analyzing high-frequency keywords, which provided in-depth insights into the literature. The cluster analysis conducted using CiteSpace has uncovered emerging trends and patterns that offer a unique and comprehensive perspective on potential research directions.

Nonetheless, this article, like any others, concedes its drawbacks due to the research methodology used, which resulted in a restricted sample of relevant publications. Firstly, the data collection was confined to one database (WoS core collection), which may have excluded valuable results. Therefore, it is recommended that future research broaden the scope of the study by accessing multiple international databases (e.g., Scopus, or IEEE Explorer). It is worth mentioning that the dataset used in the study only covered articles from 2017 to early 2022, omitting earlier publications. Furthermore, this study focused exclusively on journal articles and review papers, disregarding other relevant materials such as conference proceedings, books, and chapters that could have potentially contributed to a more comprehensive analysis. While the Bibliometrix R package, CiteSpace, and VOSviewer are popular bibliometric research tools, they have certain limitations, and it may be worthwhile for future research to consider using other tools such as BibExcel, HistCite, and Gephi for a more comprehensive review and improved visualization. Another important consideration is the need to differentiate between the popularity and prestige of research papers, which can be addressed through page rank analysis. Moreover, the specific keywords used in the search query can impact the resulting sample and subsequent analysis, and using alternative keywords may yield new insights. Lastly, it should be emphasized that the field of AI and blockchain integration is rapidly evolving, and new developments are expected to generate new avenues of research. Therefore, it is important for researchers to remain up-to-date on the latest advances in this field. Despite the limitations outlined above, the findings presented in this article undoubtedly open up ample room for future research opportunities.

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