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Overview of Blockchain Oracle Research

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ABSTRACT: Whereas the use of distributed ledger technologies has previously been limited to cryptocurrencies, other sectors—such as healthcare, supply chain, and finance—can now benefit from them because of bitcoin scripts and smart contracts. However, these applications rely on oracles to fetch data from the real world, which cannot reproduce the trustless environment provided by blockchain networks. Despite their crucial role, academic research on blockchain oracles is still in its infancy, with few contributions and a heterogeneous approach. This study undertakes a bibliometric analysis and aims to shed light on the institutions and authors that are actively contributing to the oracle literature, intending to promote progress and cooperation. On the one hand, although worldwide collaboration is still lacking, various authors and institutions are working in similar directions. On the other hand, most areas of research are scarcely explored, and others are even untouched.

Keywords: Blockchain; Smart Contracts; Oracles; Bibliometric Analysis

1. . INTRODUCTION

"Although oracles play a critical role … the underlying mechanics of oracles are vague and unexplored" [1]. A preliminary study on Decentralized Finance (DeFi) oracles from the University of Singapore shows that despite the massive amount of money managed by oracles on DeFi platforms, their functions and roles are still widely neglected. Despite the plethora of papers involving blockchains, less than 15% consider oracles, and an even smaller percentage further investigates related issues [2]. The subject of blockchain oracles is critical because the whole concept of blockchain applications revolves around the idea of decentralization and trustless transactions. Those pillars, however, are undermined while gathering real-world data; blockchain applications rely on centralized and trusted third parties. This issue, either addressed as an oracle problem [3] or an oracle paradox [4], makes the community of blockchain enthusiasts quite skeptical about real-world applications [5]. Proposing a robust blockchain application against the oracle problem requires the redaction and discussion of the so-called "trust model," a document or scheme that broadly explains how data are fetched by oracles in a decentralized and trustless way [6]–[9]. Defining and adopting a robust trust model is not only essential for a blockchain application to work properly but is also often considered the key to mass adoption [10]. However, academic contributions concerning oracles or those discussing a detailed "trust model" [2] remain scarce. On the one hand, proposing a real-world blockchain application without analyzing the oracle's role in depth poses serious doubts about the feasibility and genuineness of the underlying project [11]. On the other hand, proposals with a detailed trust model would greatly help researchers and practitioners analyze oracle-related features and issues and reproduce successful projects, respectively [12].

Therefore, knowing which institutions are actively undertaking research on blockchain oracles and which ones are already implementing them in real-world applications is interesting and important. Scholarly interest in blockchains has resulted in some literature reviews on this topic, but none has yet undertaken research through a bibliometric analysis on blockchain oracles [13]–[15]. A bibliometric analysis aims to identify how the body of knowledge on blockchain oracles has evolved in the last few years in terms of the leading publication outlets, the geographical distribution of research communities, the density of collaboration, and methodological approaches. Unlike classic literature reviews, a bibliometric analysis provides a quantitative and structural overview of the investigated scientific field, reducing the chances of subjective biases [16]. The advantages of undertaking this type of study are the representation of a phenomenon in a formal and objective way, ensuring the robustness and reproducibility of results. A bibliometric analysis is also meant to guide scholars who are interested in undertaking research in that sector to understand the research gaps, methodologies used, and appropriate outlets for publication. To ensure the significance, usability, robustness, and replicability of the research, this paper will follow a standard bibliometric approach that has been used in several studies across different disciplines [17]–[21]. The methodology will be extensively explained so that any individual can reproduce every passage, regardless of their expertise. The data extracted will be motivated by the associated meaning and will be presented with the aid of figures and tables. Following prior bibliometric analyses in other sectors, the collected sample will be organized based on the categories and sub-categories of the topics [20], [22]. In this study, three areas will be investigated. First, an overview of the most productive institutions (in terms of papers published), along with the most cited authors, will be provided. Second, an analysis of the most common publication outlets, publishers, and paper types will be provided to ease the publication process. The authors will then have a better overview of the venues that support research in this domain. Third, ongoing studies will be further investigated to identify common streams of research, methodology, and findings to incentivize cooperation and progress in the field. The following are the objectives of the study:

OBJ 1) Identify the most cited authors and productive institutions to find institutions and authors focused on the subject of the study.

OBJ 2) Highlight the most common outlets, publishers, and paper types to ease the publication process.

OBJ 3) Find studies that investigate similar research domains to promote cooperation and progress.

We consider this study necessary, given the massive resonance of blockchain-related research and the slight growth in oracle-related investigations [12], [13]. This study will help researchers and entrepreneurs know which institutions are actively involved in a specific real-world blockchain application, how oracles are implemented, and how the oracle problem can be efficiently addressed. Building on the author's previous studies that have already discussed oracle limitations can improve the quality and speed of research in related fields [2], [23].

To better understand the value and contribution of this paper, we should point out that real-world blockchains to which this study refers are applications other than cryptocurrency, such as healthcare, supply chain, DeFi and resource management. Therefore, specific studies on blockchain characteristics, ecosystems, and cryptocurrencies are not considered in this paper because they are not directly related to blockchain–oracle ecosystems. Furthermore, a certain degree of subjectivity, especially in the selected categories, cannot be excluded despite the rigorous research design. Given the absence of prior studies, a predetermined framework was also not available to build upon. Given the scarcity of data and the increasing academic interest in the subject, the data presented in this study may also face early obsolescence.

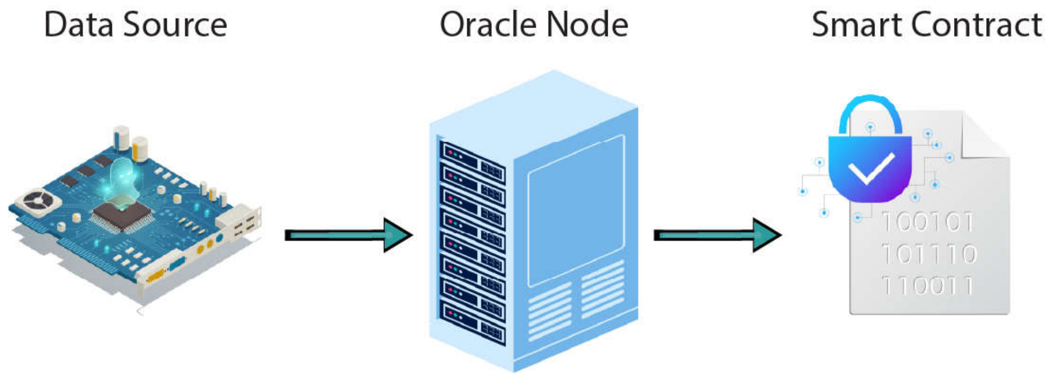
This paper is organized as follows: Section 2 covers the literature background, and Section 3 outlines the methodology. Section 4 summarizes the results, and Section 5 discusses possible institutional cooperation based on the studies and methodologies used. Section 6 concludes the paper by providing hints for further research.

2. LITERATURE BACKGROUND

The power of Bitcoin lies not only in its decentralized features but also in its programmability. Experts, such as Antonopoulos, address it as "programmable money" [24]. Just by using "scripts" and without the intervention of third parties, premade "agreements," such as timelocks, Pay-to-Script-Hash, multi-signatures, can be executed on transactions [25]. However, because of Vitalik Buterin and the introduction of the Ethereum virtual machine with smart contracts, blockchains became more developer friendly and could be easily programmed for applications above the simple exchange of cryptocurrencies [5]. Nonetheless, the Ethereum blockchain needs to be a closed ecosystem operating on data that are already on the blockchain to reproduce Bitcoin's trustless and deterministic setting [5]. This condition is necessary to ensure that all the required data for smart contracts are publicly verifiable and auditable by all nodes [5], [26]. Without the data coming from the external world, the range of possible automated contracts would have been extremely limited [27]. Therefore, a means to deliver extrinsic data to the blockchain was needed to broaden the use of smart contracts, [3], [28], [29]. This method is called an oracle. The oracle is an entire ecosystem that permits the collection from and the transfer and insertion of external data to the decentralized application [30], [31]. As displayed in Figure 1, the oracle ecosystem usually comprises the following three parts.

Data Source: This is the source from which the data are collected and stored. It may or may not eventually be used by a decentralized application. The data source can be a Web Application Programming Interface (API), a sensor, or a human aware of a specific knowledge or event [32].

Figure 1. Oracle ecosystem.



Communication Channel: This is usually referred to as "node." It collects the data from the data source and delivers them to a smart contract so that the latter can be executed. Sometimes, oracle nodes coincide with blockchain nodes, but this is not always the case [27], [33].

Smart Contract: This contains the code that establishes how the collected data can be managed. Usually, it has prespecified quality criteria for data to be accepted or rejected. If necessary, it may also perform computations to deliver the appropriate data to the contract [34], [35].

Depending on how these three parts are organized and interact with each other, multiple types of oracles can be designed [10]. These three parts of an oracle are not always separate from each other, as the same entity may sometimes cover two or three roles at once. A human, for example, can serve as a data source and communicate the data directly to a smart contract [36]. In actuality, having more than one entity that covers the role of data source/node is possible and desirable. Relying on multiple entities is, in fact, crucial to ensure the execution of smart contracts, especially when one or more data sources/nodes are malfunctioning or offline [37].

The above-described oracle ecosystem is typical of blockchains that support smart contracts (e.g., Ethereum, Tron). Instead, oracles are implemented differently for blockchains, such as Bitcoin, where smart contracts (apart from a few scripts) are unavailable. If smart contracts are unavailable, oracles are usually implemented through M-of-N (e.g., 3 out of 5) multisignature wallets, requiring more than one signature to broadcast a transaction [38]. Therefore, the owner of a key plays the role of an oracle and executes the transaction when a certain condition is met. In that case, the oracle covers both the role of the node and the data source—for example, an agreement that sets a payment upon the delivery of a parcel (Figure 2).

Figure 2. M-of-N Oracle Example.

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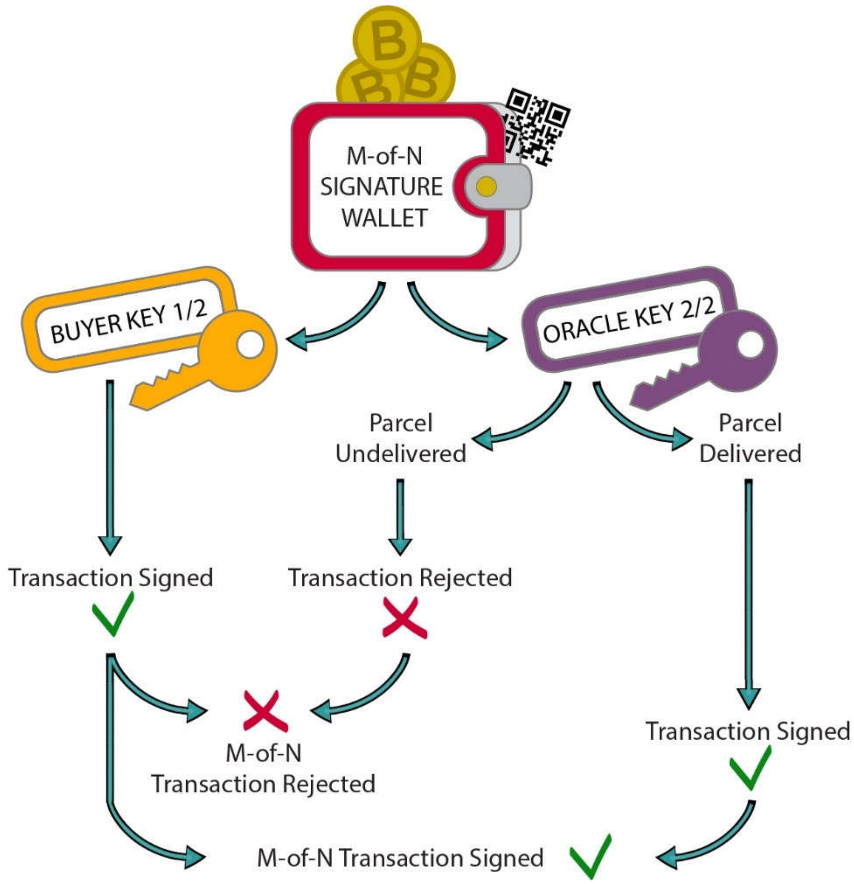

A multi-signature wallet must be set up in which one of the keys has to be entrusted to a third party that performs the role of an oracle. When the buyer acquires the product, she signs the transaction with her key. However, given that the second signature has not been inserted, the transaction remains on hold. When the parcel is delivered, the entity in control of the oracle key signs the transaction, allowing for successful execution of the transaction. Evidently, the choice of the entity that possesses the oracle key plays a crucial role in those types of ecosystems [3]. This is a trivial example of an oracle solution on the Bitcoin blockchain implemented in traceability; however, the most commonly used cases belong to the finance/gambling field [39].

A thorough explanation of all oracle types is beyond the scope of this study; however, further information can be found in dedicated papers and web articles listed in references [10], [31], [40], and [41]. Given that oracle ecosystems operate in a different way with respect to blockchains, characteristics such as immutability, transparency, and trustless execution are not ensured [42]. This discrepancy in attributes implies that when blockchain-based applications need data from the external world, the characteristics of oracles are to be taken into serious consideration. If the data source is unreliable, the node is not trusted (or private), and the smart contract is poorly audited, the fact that an application runs on the blockchain is practically irrelevant [3], [12], [43]. Depending on third parties, blockchain technology alone cannot represent a solution to centralization, trust, and security issues.

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This condition, widely explained by blockchain experts such as Andreas Antonopoulos and Paul Sztorc [44], [45] and labeled by Dalovindj [39] as “the oracle problem,” must be considered at the time of integrating blockchain with applications in the area of the supply chain, healthcare and academic credentials. Various consequences may be faced, depending on the faulty oracle part and the application type [12], [36], [46]. In the healthcare sector, the presence of oracles constitutes another possible source of data breach, exposing patient records to theft or manipulation [47]. In the DeFi sector, the dependency on oracles would expose decentralized applications that rely on centralized or insecure data sources to risk millions of dollars of invested capital [46], [48].

In the traceability sector, blockchain technology has been proposed, relying principally on the misconception that considering that the origin and movement of a cryptocurrency on the blockchain can be traced in a secure and trustless manner, the same can be done with a tangible asset, such as food, clothes, and medicine [44]. Because dependency on oracles for real-world applications makes it unlikely to reproduce the same level of tracking accuracy, only a few traceability projects show some robustness against that issue [8], [42]. Lately, with Non-Fungible-Tokens (NFTs) and stablecoin technology, the blockchain-based traceability of tangible products is also following another path [49]–[51]. Rather than directly tracking a real product with blockchains, companies are instead creating a representation of those on the blockchain (NFTs) to guarantee genuineness and ownership.

Because of the oracle problem, numerous critiques and concerns also arise for other blockchain applications, such as intellectual property rights management, e-government and resource management [28], [52]–[54].

For these applications to run genuinely decentralized and trustless, oracle ecosystems should be structured to ensure the same characteristics as blockchains. However, unlike blockchain technology, which has a history and development of nearly thirty years (considering the work of Haber and Stornetta [55] as its precursor), oracle ecosystems are relatively newer and unexplored spaces with few actors and limited literature [2]. This is the gap in which this study finds its legitimacy. It aims to shed light on academic contributions concerning blockchain oracles and promote cooperation and progress.

3. . METHODOLOGY

An appropriate methodology should be chosen to fulfill the purpose of this study. Furthermore, an in-depth description of the steps followed had to be provided to ensure the reproducibility of the results. A bibliometric analysis was perceived as the appropriate method for reaching the goals of this research. Also, its standardized and systematic approach would ensure the reproducibility of results [17], [56]. Building on prior bibliometric analysis [57], [58], the methodology description will first involve database selection, inclusion, and exclusion criteria and, finally, data extraction variables. Regarding the data collection, the intention is to include as many articles as possible, as long as they are of an academic nature. Therefore, gray literature, such as whitepapers, opinion posts, and news, will not be considered in this research. On the one hand, although not peer-reviewed, this analysis will also consider preprints. The reason for this choice is that the included preprints

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are written by academics for submission to academic journals. On the other hand, non-peer-reviewed material, such as opinion posts, is not meant to follow an academic path. Following Buttice and Ughetto [22] and Martinez-Climent et al. [56], the selected databases were Scopus and Web of Science (WoS), but Google Scholar was also queried. As the analysis also comprises preprints and unpublished manuscripts, limiting the research to Scopus and WoS would not have been a coherent choice. Including a third database would also increase the chance of retrieving other relevant articles. For the three databases, the research was conducted on March 02, 2022. When "blockchain" and "oracle" were used as keywords in the TITLE-ABS-KEY of Scopus database, 312 articles were identified. In the WoS database, two strings were implemented in the "Topic" section so that articles containing the word "oracles" were also included and identified. The research returned 143 results. The Google Scholar database was queried using the same keywords as those used on the Scopus database, but the queries returned more than 10,000 entries because of their structural differences with Scopus and WoS. For that reason, and due to saturation of results, the author decided to stop the research on Page 35 (which presents 350 entries organizing results in ten per page). Table 1 summarizes the queried databases, along with the selected research strings. Appropriate exclusion criteria were adopted to narrow down the most appropriate data sample, with the aim of balancing inclusiveness with relevance. However, no restrictions based on language or timeframe were applied because of the nascency of the topic and the research goal. Given that the goal was to gather all the relevant information about oracle research, related authors, and institutions, adding a time or language restriction was a coherent choice.

Table 1. Databases and Research Strings.

Database	Research String
Scopus	(TITLE-ABS-KEY (blockchain) AND TITLE-ABS-KEY (oracle))
Web of Science	blockchain oracle (Topic) and blockchain oracles (Topic)
Google Scholar	blockchain, oracle (anywhere in the article)

First, the abstract and introduction were read to retrieve and exclude evidently off-topic papers. Many documents were included in the sample for mentioning "random oracles" or "test oracles," which, despite a similar name, were not the oracles on which this study investigates. Other papers that mention Oracle, the name of a company, were also included, which, although involved in some blockchain projects, is again unrelated to the oracles discussed in this study. After following these steps, 163, 69, and 189 articles were removed from the Scopus, WoS, and Google Scholar samples, respectively. Given that gray literature was also retrieved from the Google Scholar sample, 7 other articles were removed because they were neither written by academics nor published in academic venues. After duplicates were removed, the three samples were merged, obtaining a nonredundant sample of 282 entries.

With the steps mentioned above, the obtained sample was composed of papers that included the "oracle" keyword and specifically referred to the communication channels between the blockchain and the real world. However, the aim of this paper was to present the portion of literature that not only mentioned the oracles or explained their use but also offered a direct contribution to the oracle literature. Therefore, to further skim the results, all PDF articles were downloaded and inspected one by one with a word processor. All occurrences of the word "oracle" were contextualized and analyzed. The criterion was that if oracles were mentioned in the introduction or literature review but did not constitute a central part of the analysis, the article was not included in the sample. To better explain this research step, the table in Appendix A provides a list of the research and inclusion criteria.

With this criterion, nearly half of the sample (120 papers) were discarded. Therefore, the final selection was reduced to 162 entries. In summary, because of these research steps, articles that not only mentioned blockchain oracles but also discussed their role and contributed to their development were retrieved. Table 2 broadly summarizes the methodology followed.

Table 2. Research steps.

Steps	**Databases**			**Total**
	Scopus	Web of Science	Google Scholar	
Papers are retrieved using research strings	312	143	350*	805
Off-topic papers are removed	163	69	189	–421
Duplicates are removed				–102
Unrelated papers are removed				–120
Final sample				162

3.1. DATA EXTRACTION

Appropriate extraction variables (displayed in Table 3) were identified to extract as much information as possible from the selected sample. As is probably the first bibliometric analysis on blockchain oracles, building upon existing or prior research was impossible. However, given that the aim of bibliometric analyses is relatively homogeneous, extraction variables could be taken from similar papers investigating other literature domains [22], [56], [59]. First, the "year of publication" is considered to place the literature within a specific timeframe, whereas the "element type" shows the most usual outlet for retrieved publications. "Authors," "institutions," and "countries" of provenance geographically contextualize the paper sample, highlighting the contributors to the academic advancements in the sector.

Table 3. Extraction variables.

Variable	**Description**
Category	The research field of analysis
Item Type	Journal, conference, book chapter, or preprint
Year	Year of publication
First Author	Name of the first author
Authors	Full author list
Title	Title of the paper
Citations	Google Scholar citations
Outlet	Name of the journal/conference/book

Publisher	Name of the publisher
Keywords	Indexing keywords
Country	Country of the first author
Continent	The continent of the first author
Institution	Institution of the first author
Study type	Theoretical, empirical, or review

Citations and keywords were used to analyze metrics. Finally, as in Butticè and Ughetto [22], articles were further divided based on their specific fields of analysis. This categorization of papers serves to investigate whether streams of literature exist where researchers are more contributing and others that require more attention. Although it may constitute a bias, in line with prior research, articles were associated with only one field category to avoid double entries [22]. First, two main categories were identified, mainly to distinguish between studies concerning oracles themselves and oracles applied to other sectors.

Second, the papers were divided to further differentiate them based on their specific fields of analysis. Although inspired by related research, category selection embodies a certain degree of subjectivity. Therefore, a description of these categories, starting with the main ones, is provided hereafter.

Oracle Theory (OT): Under this category, papers specifically focused on blockchain oracles, either from a theoretical or a practical point of view, were included.

Oracle Applied (OA): This category included papers that focused on real-world applications, such as healthcare, finance, and business process management, and also provided a detailed analysis of the role of oracles in these fields with theoretical or experimental approaches.

The main categories were further divided into sub-categories. Hereafter, those that belong to OT are listed as follows:

Architecture: With an empirical or theoretical approach, papers in this category performed analyses on the oracle framework to improve technical aspects, highlight current challenges, and identify new avenues for research. Unlike proposals or OA papers, this group includes works that have investigated existing oracle schemes that are not directly applied to a specific sector.

Proposal: These papers propose new oracle frameworks that may be implemented in real-world applications. These may still be at a conceptual or prototype stage.

Oracle Problem: These articles focused on aspects related to the trustworthiness of oracles and their limits to decentralization. Whereas all papers should outline trustworthy oracle environments, the papers in this category focused on the involved actors' incentives to cheat and the consequences of a deviation on the underlying applications.

Sub-categories belonging to OA, such as healthcare and energy, are intuitive, but those that require clarification are described hereafter.

Data Management: Articles concerning the transfer of data from the real world to blockchain pertain to the main category of OT. In this field, articles that analyzed access data management for reputation, privacy, or GDPR purposes were considered. Cloud-computing-related research was filed under its own category, given that it mainly concerned data elaboration.

Finance: In this category were grouped articles that involved oracles applied in financial applications and those that explored timeliness and gas usage of transactions. Those concerning asset management on blockchains were also included.

IoT: This category comprised papers investigating oracles as efficient IoT systems but did not refer to a specific real-world application. A paper concerning IoT in the supply chain, for example, would instead be inserted into the "supply chain and traceability" category.

Business Process Management: This category included works that proposed blockchain integration in business processes, clearly identifying the role of oracles. Although supply chain is part of the business processes, articles specifically investigating this field were filed under their own categories.

Artificial Intelligence: Papers filed under this group concerned research toward the integration of blockchain technology into existing AI tech through the use of oracles or AI to improve oracle efficiency and reliability.

Transport: This category included papers investigating blockchain integration into intelligent vehicle development and the transport industry in general. Research on IoT device/sensors specifically implemented in the transport field were also filed in this category.

Supply Chain and Traceability: Papers investigating the benefit of integrating blockchains in the local or global supply chain belong to this category. Also included were works that concerned the traceability of physical products or documents. Works investigating the traceability of financial assets (e.g., stocks or crypto) were included instead to the finance field.

Only the first author was taken into consideration to extract the country and institution provenance of the paper. Considering all the authors would have created a bias toward articles with a higher number of authors. We were aware that this choice may eventually affect the final results, but any other option would have done the same. Regarding the authors' affiliation, the choice was to take the one declared in the last published paper to avoid the problem of double affiliation. With this criterion, some affiliations may have changed by the time the paper was published. Finally, citations were taken from Google Scholar because it was the only database in which all the papers in the sample could be retrieved. We were aware that prior studies cited in this paper utilized ad hoc programs, such as VOSviewer, for the elaboration of the result graphs. However, considering the extremely limited size of the retrieved sample, Excel tables and charts were considered to be much more intuitive. Furthermore, considering preprints from Google Scholar, software such as Bibliometrix could not be implemented. Therefore, a non-automated analysis was perceived as the most reasonable option.

4. . RESULTS

In this section of the paper, the results of the bibliometric analysis are reported. With a quantitative approach, the status and trends of the literature on blockchain oracles are shown. The analysis first covers the time and space of the research and then focuses on the outlets, authors, and field of analysis.

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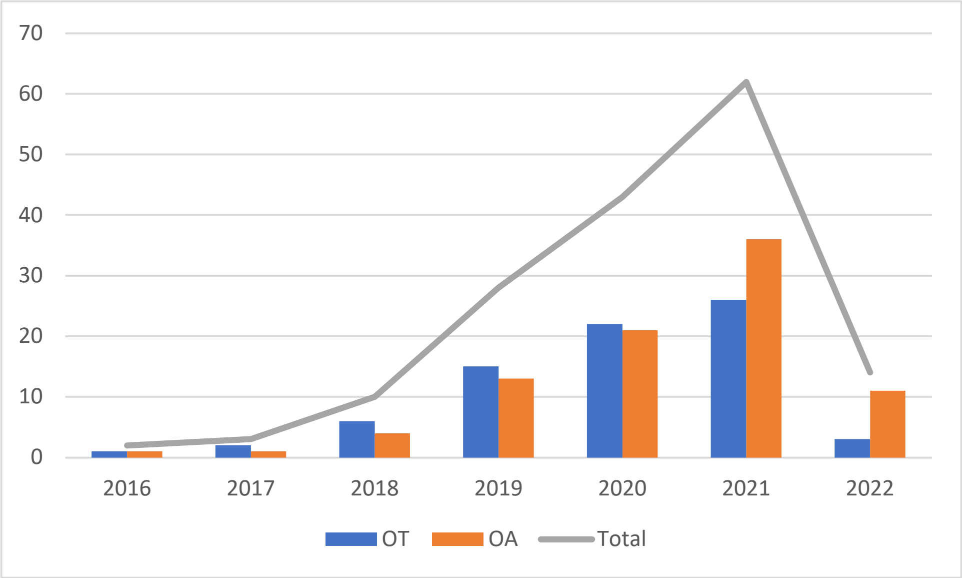
4.1. NUMBER OF PUBLICATIONS PER YEAR

The first academic papers considering blockchain oracles appeared in 2016 and were equally distributed among the categories "oracle theory (OT)" and "oracle applied (OA)" [60], [61]. As Figure 3 shows, interest in the topic remained low until 2018. Until 2019, the number of papers concerning OT were slightly more than those discussing OA. The increase and the shift in the trend can be observable from 2019, with 2020 having four times more publications than in 2018 and 2021 having more than double the number of publications of 2019. Moreover, the number of papers regarding OA started to exceed that of OT by 2021. Although the 2022 sample concerns only the first two months, the imbalance in the number of publications appears to be confirmed. These data reveal that the topic has gained more impact and attention among academics, probably because of the higher developments of blockchain-related platforms.

Figure 3. Publications per year.



However, in absolute terms, the overall numbers remain low, with a peak of 62 publications in 2021 and only 162 publications in all six years of academic production. These numbers show that this is still a niche subject.

4.2. PRODUCTIVITY RATE BY GEOGRAPHICAL DISTRIBUTION

Tables 4 and 5 present the distribution of papers by country and continent, respectively. We can observe that the continents with the highest productivity are Europe and Asia, with more than 70% of total paper production. Asia, however, appears to be more focused on OA than Europe, which, although with practically the same OA contributions, presents a balance between the two main categories.

Table 4. Distribution among the ten most productive countries.

Country	OT	OA	Total
China	10	13	23
Italy	7	11	18
USA	11	4	15
Canada	7	8	15
Germany	7	7	14
UAE	1	12	13
Australia	7	2	9
France	2	3	5
Austria	4	0	4
India	2	1	3

OT = oracle theory, OA = oracle applied.

Table 5. Distribution by continent.

Continent	OT	OA	Total
Europe	31	36	67
Asia	18	35	53
America	18	12	30
Oceania	8	2	10
Africa	0	2	2

OT = oracle theory, OA = oracle applied.

Concerning countries, the situation partially reflects what is observed with continents. The most productive countries are China and Italy, followed by the USA and Canada. Only those four countries together accounted for more than 44% of total publications. Concerning fields, countries appear to be sufficiently balanced, except for the UAE, which is more focused on OA, whereas Australia, USA, and Austria mostly contribute to OT research.

4.3. PUBLICATIONS BY OUTLETS AND PUBLISHERS

As Figure 4 shows, the majority of papers published in this field are journals (73) and conference papers (60). However, a small portion consists of book sections (20) and preprints (9). These data contrast previous blockchain technology reviews, showing that the number of conference contributions is four times more than that of journal publications [2], [14].

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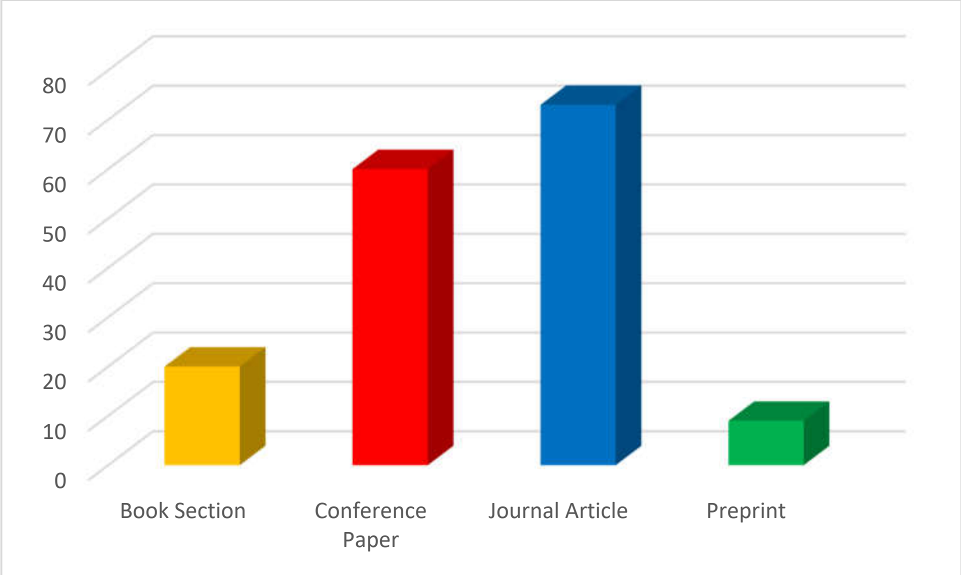
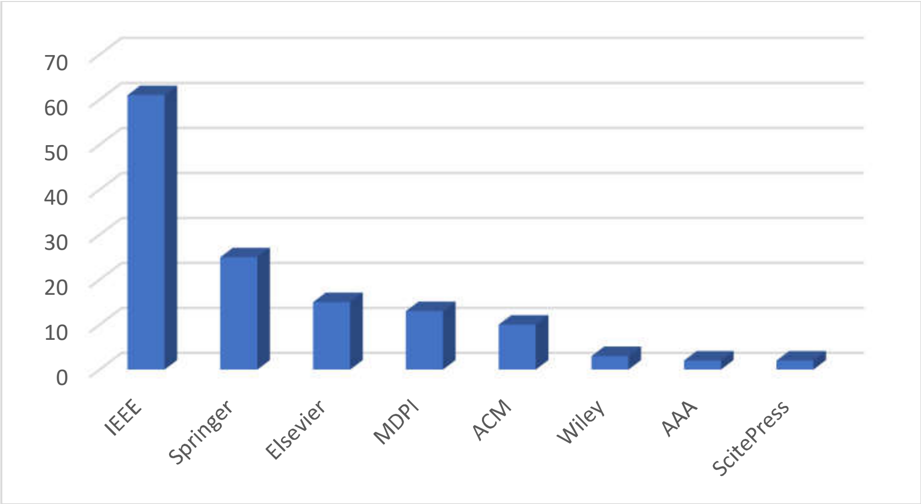
Figure 4. Publications per type.



This finding supports the idea that there seems to be no dedicated conference venue on blockchain oracles. Table 6 and Figure 5 show the distribution of papers by journal and publisher, respectively. We observed that the majority of papers (61) are published in IEEE outlets and venues, whereas 25, 15, and 13 papers are published in Springer, Elsevier, and MDPI, respectively. However, if we consider only journal publications, the weight of the contributions would slightly change, given that 43 IEEE documents were conference papers, and of 25 Springer entries, 20 were book sections.

Figure 5. Documents by publisher.



Then, excluding non-journal publications, we would have IEEE with 18 publications, followed by Elsevier with 15, MDPI with 13, and Springer with 5. This information is incredibly insightful when considering Table 7, which shows that only four journals published more than two papers on the subject.

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Conference venues and book sections, except for two venues, contributed with no more than one document.

As shown in Table 6, the journals that published more contributions are *IEEE Access* and *Future Generation Computer Systems*, both with eight contributions. Among the other venues, the only notable is *Business Process Management: Blockchain and Robotic Process Automation Forum*, which contributed five book chapters.

Table 6. Documents by Journal/Venue.

	Journal/Venue Name	Publisher	Contributions
Journal	IEEE Access	IEEE	8
	Future Generation Computer Systems	Elsevier	8
	Applied Sciences	MDPI	3
	IEEE Internet of Things Journal	IEEE	3
Conference	2019 IEEE International Conference on Blockchain and Cryptocurrency (ICBC)	IEEE	2
	2021 IEEE Information Theory Workshop (ITW)	IEEE	2
Workshop	Business Process Management: Blockchain and Robotic Process Automation Forum	Springer International	5
	Financial Cryptography and Data Security. FC 2021 International Workshops	Springer Berlin Heidelberg	2

4.4. *ARTICLE TYPE FIELDS AND KEYWORDS*

Table 7 provides an overview of the paper types determined by fields based on the main categories and sub-categories indicated in the Data Extraction (3.1) section. It emerges as more than half (103); precisely, 63% are empirical papers, 23% are theoretical papers, and 14% are reviews. At the general level, the majority of academic research over oracles is of an empirical nature. Nevertheless, these data still need to be distinguished by field of research.

Concerning division by category, despite the higher number of sub-categories, the total number of papers belonging to OT (75) is slightly below those on OA (87). This is understandable, considering that oracles are still in their early-stage development, and a heterogeneity of views on how they should function and operate still exists. Although the majority of articles are still empirical, they are well balanced with theoretical and review types for the "architecture" and "oracle problem" sub-categories.

The second thing that emerges is that proposals are mainly of empirical/experimental nature, which bodes well for the birth of oracle frameworks in cooperation among or fully developed by academic institutions.

Table 7. Distribution by category and article type.

Field		Article Type			Total
Main categories	**Subcategories**	**Empirical**	**Theoretical**	**Review**	
Oracle Theory	Oracle Problem	6	6	6	18
	Proposal	19	3	0	22
	Architecture	18	8	9	35

Oracle Applied	Finance	16	2	4	22
	Data Management	9	5	0	14
	IoT*	9	2	1	12
	BPM*	4	3	1	8
	Supply Chain & Traceability	6	1	1	8
	AI*	4	3	0	7
	Cloud Computing	4	1	0	5
	Healthcare	4	0	0	4
	Transport	2	2	0	4
	Energy	2	1	0	3

*IoT = Internet of things, BPM = business process management, AI = artificial intelligence.

Regarding "oracle applied (OA)" papers being ideally a more practical area compared to OT, why an imbalance (except for BPM, AI, and transport) exists between empirical and theoretical papers is understandable. Furthermore, the smaller category size explains why only seven review papers were retrieved. By analyzing sub-categories, we can observe that some areas have fewer contributions than others. The finance sector is leading, with 22 contributions, followed by data management (14) and the IoT (12). Given the higher advancement level of blockchain applications in these sectors and the empirical nature of academic contributions, why other sectors, such as healthcare, transport, and energy, have less than five contributions is also understandable.

Keywords are also an important parameter to consider when evaluating a sample. A total of 650 keywords were extracted from the sample, which means a media of 3,9 per article. While some articles had six or more keywords, others (mainly preprints) had none. After duplicates and plurals were removed, 307 unique keywords were found. To avoid biases with the research strings used, however, we excluded keywords such as "blockchain" and "oracle(s)" from the analysis. Keywords composed of multiple words (e.g., Smart Contract) were considered unique, and those composed of banned keywords, such as "price-oracles," were not excluded. The choice to leave keywords composed of the two banned words lies in the idea that, while those keywords alone are common for all papers, composed keywords, such as centralized oracle or blockchain interoperability, are proper in specific sectors, which will benefit from homogeneous keyword usage. Plurals were also merged with singular forms (e.g., contract/contracts). Figure 6 shows the word cloud made with all the keywords in the sample. Notably, the most frequently used keywords are smart contract and Ethereum, with 67 and 21 occurrences, respectively. Whereas the keyword smart contract says very little about our sample, the recurrence of "Ethereum" surely reflects the most common study environment on oracles that appear to be the Ethereum network. Other keywords used are internet of things (8), consensus (7), and cryptocurrencies (5), whereas some have a lower currency rate. Interestingly, of the whole sample of 307 keywords, the majority (250) occurred just once. Keywords were also divided into categories to achieve good data breakdown.

Figure 6. Keywords word cloud.

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After the most common keywords (e.g., Ethereum, Smart Contract) were excluded, excessive heterogeneity was still apparent, even after dividing them by categories. Composite keywords, such as “business process monitoring” and “business process management,” were merged (e.g., business process) for consistency. In Table 8, keywords with higher occurrences divided by categories are listed. These data are useful for indexing purposes and for research to be easily retrieved by the appropriate audience. The “transport” category was excluded from the table because of excessive heterogeneity.

Table 8. Keywords by category.

Category	Keyword	Number	Category	Keyword	Number
Architecture	Architecture	3	**AI**	Artificial Intelligence	2
	Consensus	2		Machine Learning	2
	Data	3	**BPM**	Business Process	4
	Decentralized	3		Privacy	2
	Pattern	3		Service Composition	2
	Transaction	2	**Cloud Computing**	Cloud Computing	2
	Zero Knowledge Proof	2		Fog Computing	2
Finance	Cryptocurrencies	4	**Data Management**	5G	2
	Decentralized Finance	3		Certificate	2

	DeFi	3		Cross-Chain	2
	Gas	6		Data	5
	Financial	2	**Energy**	peer-to-peer	2
	Security	2	**Healthcare**	Healthcare	2
	Transaction-fees	2		Personal Health Records	2
IoT	Internet-of-things	5	**Supply chain**	Internet-of-things	3
	IoT	5		Supply chain management	3
Proposal	Consensus	3	**Oracle Problem**	Trust	3
	Decentralized Oracle	3		Real-World	2

4.5. CONTRIBUTION BY AUTHOR/INSTITUTION AND METRIC

The most cited papers, authors, and contributing institutions are displayed in Tables 9, 10, and 11, respectively. Building on prior bibliometric analyses [62]–[65], the papers were ordered in terms of citations; therefore, the ten papers displayed in Table 10 are the most cited ones. However, institutions were ordered in terms of the papers produced. The list was not limited to ten but is restricted to those who provided at least three contributions. The most cited authors were selected with a mixed approach. Ordering authors by citation would have resulted in a biased list because of papers with many coauthors and citations. Therefore, to be inserted into the list, one requirement is to have produced at least two publications and to be the first author for at least one of them. The requirement of at least two publications is to avoid the insertion of authors who have randomly contributed to a related paper. Then, assuming that the first author is the lead or the most contributing author, having first-authored a paper appears to also be a necessary requirement. However, to also provide visibility to coauthors, Appendix B shows a list of coauthors who contributed to at least three papers. We were aware that a higher number of papers produced or a higher number of citations would not necessarily imply a higher impact or contribution in the field of oracle research. Such a claim would require a thorough study of academic contributions to the development of successful oracle applications, which is beyond the scope of a bibliometric analysis. In this research, a parameter, such as citations or produced papers, will correspond to a notable interest in the produced research of an author or a major effort from the institution to investigate the related field. The retrieved parameters do not reflect or question, in any case, the quality of an author's or institution's publication.

Table 9. Ten most cited papers.

#	Title	Author/s	Year	Cit*	Institution	I/T*
1	The Blockchain as a Software Connector	Xu, Xiwei; Pautasso, Cesare; Zhu, Liming; et al.	2016	524	UNSW Sidney	CP
2	Architecture for Blockchain Applications	Xu, Xiwei; Weber, Ingo; Staples, Mark	2019	180	UNSW Sidney	BS
3	Astraea: A Decentralized Blockchain Oracle	Adler, John; Berryhill, Ryan; Veneris, Andreas; et al.	2018	121	University of Toronto	CP
4	Blockchain for COVID-19: Review, Opportunities, and a Trusted Tracking System	Marbouh, Dounia; Abbasi, Tayaba; Maasmi, Fatema; et al.	2020	107	Khalifa University	JA

5	Trust management in a blockchain based fog computing platform with trustless smart oracles	Kochovski, Petar; Gec, Sandi; Stankovski, Vlado; et al.	2019	98	University of Ljubljana	JA
6	A Pattern Collection for Blockchain-based Applications	Xu, Xiwei; Pautasso, Cesare; Zhu, Liming; Lu, et al.	2018	80	UNSW Sidney	CP
7	Trustworthy Blockchain Oracles: Review, Comparison, and Open Research Challenges	Al-Breiki, Hamda; Rehman, Muhammad Habib Ur; Salah, Khaled; et al.	2020	77	Khalifa University	JA
8	Analysis of Data Management in Blockchain-Based Systems: From Architecture to Governance	Paik, Hye-Young; Xu, Xiwei; Bandara, H. M. N. Dilum; et al.	2019	73	UNSW Sidney	JA
9	TLS-N: Non-repudiation over TLS Enabling Ubiquitous Content Signing for Disintermediation	Ritzdorf, Hubert; Wüst, Karl; Gervais, Arthur; et al.	2018	58	ETH Zurich	JA
10	Blockchain for 5G: Opportunities and Challenges	Chaer, Abdulla; Salah, Khaled; Lima, Claudio; et al.	2019	55	Khalifa University	CP

*Cit = Citations (Google Scholar), I/T = Item Type, CP = Conference Paper, JA = Journal Article, BS = Book Section.

As explained, information gathered with the above-mentioned approaches is provided in separate tables for clarity, but they should be discussed together to better grasp the meaning of the data.

The most cited author is Xu Xiwei (908 citations) from the University of New South Wales (UNSW) CSIRO-DATA61. She had co-authored the first two most-cited papers and four among the first ten. She started contributing to the subject in 2016, and given that her last paper on the topic was published in 2021, she appears to be still investigating the subject. All the included papers published by the UNSW are first-authored by her, except for one by Lo Sing Kuang, who is also among the most cited authors (116 citations). UNSW ranks third among the most productive institutions, with research mainly focused on oracles' architectures. The second most cited author is John Adler from the University of Toronto, who authored the third most cited paper (133 citations). In the University of Toronto, Merlini Marco is also among the most cited authors, and this institution is particularly focused on investigating decentralized oracle mechanisms. The sixth and seventh most cited authors are Omar Ilhaam A. and Al-Breiki Hamda from Khalifa University, with 107 and 97 citations, respectively. From the same university are also Battah, Ammar, and Madine, Mohammad Moussa, who are also among the most contributing authors but with fewer citations (50 and 49, respectively). Notably, Khalifa University is the most productive institution in the field, with 13 documents produced, of which 3 were among the ten most cited and 4 were among the first twenty. Observing the coauthorship, apart from the four most cited first authors, many other authors from the same university also participated in the research. Among them, Muhammad Habib Ur Rehman and Davor Svetinovic are the most cited, with 144 citations each. These findings give an idea of institutions that are heavily investing in this sector. Furthermore, this institution contributed at least one paper to every oracle application category (except for business process management [BPM] and energy). Furthermore, besides offering contributions to the healthcare and data management fields, they also produced research to address the oracle problem. Also focused on addressing the oracle problem is the University of Verona, which is ranked second by the number of articles produced.

Table 10. Twenty most-cited authors.

#	Name	Institution	Documents	Citations
1	Xu, Xiwei	UNSW, CSIRO-DATA61	6	908
2	Adler, John	University of Toronto	2	133
3	Lo, Sin Kuang	UNSW, CSIRO-DATA61	2	116
4	Kochovski, Petar	University of Ljubljana	2	115
5	Caldarelli Giulio	University of Verona	5	109
6	Omar Ilhaam A.	Khalifa University	2	107
7	Al-Breiki, Hamda	Khalifa University	2	97
8	Liu Xiaolong	Fujian Agriculture and Forest University	2	54
9	Carminati Barbara	University of Insubria	3	50
10	Rondanini Christian	University of Insubria	3	50
11	Battah, Ammar	Khalifa University	3	50
12	Madine, Mohammad Moussa	Khalifa University	3	49
13	Beniiche, Abdeljalil	INRS Montreal	2	44
14	Moudoud, Hajar	Sherbrook University	3	34
15	Tucci-Piergiovanni Sara	CEA-LIST	2	30
16	Di Ciccio, Claudio	Sapienza University of Rome	3	29
17	Ellul, Joshua	University of Malta	3	29
18	Merlini Marco	University of Toronto	2	26
19	Yeh, Lo-Yao	National Chi Nan University	2	18
20	Pierro, Giuseppe	University of Cagliari	2	17

However, publications from this institution are relatively recent and are not among the top-cited publications. From the same country (Italy), the University of Insubria is also among the most productive institutions, and two authors, Carminati Barbara and Rondanini Christian, are among the most cited (50 citations each). Works from this university and its researchers were mainly concerned with OA as an IoT in business processes. Another notable institution is the University of Ljubljana, whose contributions focus on cloud/fog computing and the oracle problem. The institution also belongs to the fifth most cited paper [66] and the fourth most contributing author, Petar Kochovsky, with 115 citations.

Among the most productive institutions, five other institutions emerged, whose researchers were also among the most impactful ones. These institutions include Beijing University, Technische Universität Berlin, the University of Potsdam, and the Institut national de la recherche scientifique (INRS) of Montreal. Beniiche, Abdeljalil from INRS of Montreal, is the most cited in this group (44 citations), and his main contributions focused on OT. Finally, from Technische Universität Berlin is Ingo Weber, which, although not the first author of any of the papers in the sample, has coauthored some of the most cited ones (303 total citations).

Table 11. Most productive institutions.

#	Institution	Number	OT	OA
1	Khalifa University	13	1	12
2	University of Verona	8	5	3
3	UNSW, CSIRO-DATA61	6	5	1
4	University of Toronto	5	5	0
5	Beijing University	4	2	2
6	Technische Universität Berlin	3	1	2
7	University of Insubria	3	0	3
8	University of Ljubljana	3	1	2
9	University of Potsdam	3	0	3
10	INRS Montreal	3	1	2

5. CONVERGING STUDIES

Before collecting and observing the data, the idea is to undertake a social network analysis to show the cooperation between authors and institutions worldwide. With this approach, with more than a single author or institution working on a specific oracle aspect, a network of specialized researchers/institutions would have emerged. The ideal result should have shown multiple papers on the same subject, written in cooperation by researchers from different institutions. Once the data were collected, however, this approach was not feasible. First, the sample was too limited for the results to be significant. Second, considering the most contributing institutions, the research produced was essentially conducted in cooperation with authors of the same department or with branches of the same university. For example, taking into account the papers produced by Khalifa University (the most productive institution), only five involved coauthors from other universities, and those coauthors were not retrieved in other papers. With even smeller samples from other universities, any retrieved information of this kind would have been highly questionable. Therefore, instead of searching for already active collaborations, the idea is to promote cooperation between institutions on the basis of the similarity of investigated subjects and applied methodologies.

5.1. ORACLE THEORY

Subjects pertaining to the OT and the oracle architecture comprise many different studies. A group of studies has been dedicated to investigating common patterns that emerge from oracle architectures with the aim of classification and improvement [40], [67]–[70].

Whereas the studies of Macquarie University [40] and UNSW are theoretical [68], [70], a study presented by Vienna University uses case distinctions that are also based on oracles' characteristics and gas usage [67]. However, in contrast to the research of Macquarie University, the papers of UNSW and Vienna University seem to follow a similar approach to distinguishing oracle patterns.

Two other studies from UNSW and the University of Tartu investigated a theoretical framework to determine the most suitable oracle for a blockchain application in terms of security and data management [30], [70]. Using a similar methodology, they both produced similar results. Other works from the University of Colorado [71], Jiamusi University [72], and Hong Kong University [73] focused on the security challenges of smart contracts and involved oracles. Whereas the first provides an overview of risks at a general level, the other two investigated emerging challenges in different blockchain applications. A group of works from Montana State University [74], University of Sfax [75], and the University of Cagliari [76] focused on gas-price oracle malfunctions. The work of Montana State University investigated the reasons that led to gas price oracle failures, and the study from the University of Cagliari outlined the failure rate of gas price oracles with an empirical approach. The paper from the University of Sfax compared different gas-pricing techniques with the aim of improving oracle reliability.

Another central subject in OT is the oracle problem issue, for which many contributions were retrieved. A group of papers focused on explaining the oracle problem, whereas others focused more on empirically investigating the subject to overcome the issue. Two papers from the University of Ljubljana and Max-Planck Institute introduced the oracle problem from a legal point of view [27], [28]. In this paper, the oracle's role as legal actors and their responsibility as a trusted entity were investigated. A similar discussion can also be retrieved in Mezquita et al. [77], which, however, focused on the legal audit of smart contracts. A thorough discussion of the audit of the smart contract in light of the oracle problem could instead be found in two works by Mark Sheldon D. [11], [78], which first introduced the problem of auditing contracts and then offered insights for future auditors to perform the task better.

Other papers from the University of Verona focused on investigating the consequences of the oracle problem in various sectors, such as IPRS, DeFi, supply chain, and so on. Considering the amount of money managed by DeFi platforms, financial implications are alarming [12], [46]. Singapore University has also produced a similar work investigating the reliability of DeFi applications because of their dependency on oracles [1]. Finally, studies from the Chiba University of Technology and the University of Dallas explored, with empirical data, the incentives of oracles to cheat or fail to transmit information [79], [80].

The last subject of OT pertains to oracle proposals. By definition, proposals are original; therefore, similar works should not be found for this category. This hypothesis was confirmed by reviewing the literature. Furthermore, apart from being unique, proposals were retrieved in a balanced distribution among institutions in different countries. The heterogeneity of proposals was also probably due to that aspect.

5.2. ORACLE APPLIED

Oracle applied research is focused on various sectors. As expected, because of the resonance and hype that cryptocurrencies attract, finance applications constitute the widest sample. Although multiple institutions have investigated the subject, they show similarities in their focus. Three

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studies from Concordia University, Delhi University, and Delft University of Technology focused on the role of the oracle as a means to manipulate the market, showing the possible risks connected with its use and misuse [48], [81], [82]. Whereas the first two have a more theoretical slant, the third one with an empirical approach investigates how arbitrageurs exploit oracle vulnerabilities.

Other research from the Oxford-Hainan Blockchain Research Institute and Singapore University of Technology and Design undertook empirical research focusing on "price-oracle" failures and possible attacks. The first proposed BLOCKEYE, a device able to hunt attacks on DeFi and oracle manipulations, for which the research team already presented some experimental results [83]. Using primary data, the second showed the deviance rates of four oracles services to enlighten the oracle's reliability and possible malfunctions [1]. Also focused on price oracles was research from the University of Houston, which, however, mainly investigated oracle calls by DeFi applications on the Chainlink protocol [84].

Another group of studies focused on specific financial applications (e.g., loans, exchanges, trust services); however, apart from two papers from Khalifa University and the University of Clermont Auvergne, which both investigated e-auctions, the rest had heterogeneous aims. Both studies on e-auction had an experimental approach and proposed a new auction service based on the Ethereum blockchain, specifying the role of oracles and how to overcome possible security issues [85], [86]. Finally, four papers investigated the role of oracles in cross-chain asset transfers. Whereas the first two studies from Nanjing and Beihang University proposed new schemes to increase cross-chain efficiency with an empirical approach [87], [88], the studies from the University of Verona and the University of Lisbon had a more theoretical approach and discussed the limitations of existing cross-chain systems [51], [89].

Most of the contributions to business process management applications were from the University of Insubria and the University of Potsdam. However, their focus diverged, given that the first focused on the privacy of business process transactions, and the second was oriented on the timeliness of registered transactions [90]–[94]. Both institutions adequately balanced theoretical and empirical work. Other studies from Sapienza University of Rome instead focused on how business processes can be monitored and improved using blockchain technology, discussing features and limitations of blockchain oracles [98], [99].

As for the supply chain and traceability fields, the works seem heterogeneous, although eight entries were retrieved. Construction, fashion, and food supply chain were investigated, as well as the traceability of vehicles and COVID-19 infections [97]–[99]. COVID-19 and food traceability were the only applications with two contributions, and as for Covid-19, they were both from the same institution [100], [101]. Concerning the food supply chain, the works from Queensland University of Technology and Sherbrooke University focused on the link between IoT devices and blockchains, discussing limitations and possible solutions. Whereas the first had a more theoretical approach, the second, with an empirical slant, proposed an alternative architecture to improve food supply chain efficiency [102], [104]. Convergences of the study could also be retrieved in the works of Etemadi et

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al. [103] and Sanchez-Gomez et al. [104]. The focus of these papers was to highlight the dependency of traceability systems on oracles and the consequences on reliability and security.

For healthcare, only four papers were retrieved, of which three belonged to Khalifa University and were focused on the security and access control of patients' records [105], [106]. Research by Goncalves et al. [107] focused on the same objective but proposed a specific oracle solution with the Chainlink oracle provider and Ethereum blockchain.

Seven entries regarding applications in AI were retrieved. The central focus was to exploit automation and oracles to guarantee trust in data gathering and processing. As in the original idea of the software oracle problem, the objective was to reduce external parties' intervention in automated procedures. Works from Toulouse University and INRS Montreal investigated AI-based oracles to provide non-forged results [108], [109]. Whereas the first aimed to complete the automation of the oracle ecosystem, the second proposed a more hybrid system between humans and machines. The two other works by El Fezzazi et al. [110] and Richard et al. [111] aimed to exploit blockchain features to improve machine learning processes. Both offered a theoretical overview of the blockchain implementation outcome at the concept stage.

The IoT sector has 12 publications, and the main issue of investigation is the problem faced while ensuring that the data gathered by IoT devices is trustworthy and private. Gordon [112] and Vari-Kakas et al. [113] outlined the problem of secure and trustworthy data provenance within IoT systems. Whereas the former is more structured as an essay, the latter has an empirical structure and is particularly focused on the probability for an IoT oracle to deliver reliable data to the blockchain. In response to this issue, research by Shi et al. [114] proposed a secure and lightweight triple-trusted architecture to guarantee the unforgeability of data collected by the involved parties. By contrast, contributions from Khalifa University and Insubria University approached the confidentiality of IoT data by granting users different access privileges. With similar approaches, both studies presented a converging roadmap for development [7], [115].

As for cloud computing, only five studies were retrieved. Two were published by the same institution and proposed a trustless oracle system [66], [116], focusing on service level agreement. The work proposed by Khalifa University approached the problem of ensuring an optimal fee level to balance the needs of cloud providers and users [117].

A consistent group of papers applied oracles for data management—with a focus ranging from data privacy to data consistency and data migration. As observed, papers from other categories (e.g., AI, IoT, cloud computing) also had a similar scope of investigation. Three works from the Chiba Institute of Technology, Beijing Institute of Technology, and the University of Montreal proposed a system based on crowdsensing to ensure distributed data validation [118]–[120]. The first is organized as a proposal, whereas the two others show some experimental results. Other studies from Khalifa University and UNSW have investigated how data quality can be managed and improved with multi-party authorization and reputation systems [121]–[123]. Finally, a group of studies focused on data transmission through oracles and technologies, such as 5G and 6G. Although similar in the underlying idea, they show heterogeneous purposes [108], [124]–[127].

Works in the transport sector have focused on the security, privacy [125], [128], and efficient identification of vehicles [129], as well as data processing for intensive transport environments, such as commercial waterways [130]. Whereas the work from Khalifa University discussed the implementation of Chainlink for autonomous vehicle test-case repositories, the works from other universities proposed their own oracle design for efficient data transmission in the transport industry.

Finally, three entries were retrieved for the energy sector. All three were published between late 2021 and early 2022. The shared vision aims at decentralizing the energy market, but with a different focus. Antal et al. [131] proposed an energy flexibility token to incentivize renewable energy production at the local level. Zeiselmair et al. [132] implemented a decentralized oracle system and zkSNARKs to improve renewable energy certificate allocation. Lastly, Weixian et al. [133] investigated efficient oracle designs to guarantee secure and unforgeable data transmission between actors involved in the energy market.

6. . CONCLUSION

This paper undertook a bibliometric analysis of published studies about blockchain oracles. The aim was to display publication trends along with preferred outlets and publishers. The most cited papers, authors, and the most contributing institutions are also shown. After the selected literature is reviewed, ideas on which published documents focus are finally discussed to highlight convergence among studies and promote cooperation between institutions.

The obtained results show that, within seven years of academic production, only 162 papers (including non-peer-reviewed) were retrieved in scholarly databases. This result supports the view that blockchain oracle is still a widely neglected subject, despite its crucial importance. Most of the contributions come from Europe (67) and Asia (53), in which China (23), the UAE (13), Germany (14), and Italy (18) are the most productive countries. The majority of documents are journal publications and conference papers in which IEEE, Springer, and Elsevier appear to be the preferred publishers. Furthermore, multidisciplinary, and open-access journals and publishers were preferred, given the nascency of the subject. This research also showed that, probably given the technical aspects of the subject, empirical papers are dominant over theoretical ones. Because of the scarcity of publications, reviews are also low in number.

Concerning contributions and metrics, Xiwei Xu is the most cited author in the field and has published the two most cited papers. Khalifa University, with 13 publications, is the most productive institution. The checking of authorships showed that research teams usually do not cooperate with other universities for developing research on blockchain oracles. However, the literature review revealed that some studies bear similar aims and scopes.

The present study also showed that the literature on oracles does not cover many sectors of real-world blockchains. No contributions were retrieved for entertainment and tourism, and insurance, e-government, and resource management constituted a marginal part of the sample. Previous studies have already underlined the absence of specific papers discussing oracles' roles in resource management and, particularly, energy management [2], [10], [12]. In this study, however, at least for the energy sector, three contributions were retrieved.

The findings of this research are useful for academics, students, and practitioners. They give a broad overview of the institutions, with advanced knowledge and competence of real-world blockchains. Offering an overview of institutions investigating a specific field, this study can promote cooperation between existing or entering research teams in the blockchain oracle domain. This, in turn, can constitute a reference for entrepreneurs undertaking blockchain-based projects. Students and other academics can then utilize a resource on the state-of-the-art knowledge of related fields and investigate emerging gaps (e.g., missing resource management contributions) or create other research by building on existing studies.

This paper also has limitations, given the scarcity of retrieved material that determined low numbers in absolute terms in all the tables and figures. Considering that the overall numbers are low, the dominance of specific countries or institutions will likely change shortly. As specified in Section 3, a degree of subjectivity in the presented results cannot be excluded. Whereas previous studies inspired the method and bibliometric research, the author had to select them arbitrarily. Subjectivity can also be found in the sample classification given that the division of topics into categories and sub-categories had to be performed manually. Again, the author wishes to reiterate that the data provided in this paper should not, in any case, be interpreted as a quality evaluation of the cited works. Because of the selection criteria, some works or authors may have been excluded inadvertently. Further studies can build on this bibliometric analysis to investigate the trust models adopted and presented in the published literature and the preferred oracle applications for academic investigations.

Appendix A. Relevant contribution example

Paper Title	**Oracle Contribution**	**Reference**
The limits of smart contracts	Provides an analysis of the role of oracle from a legal point of view	[28]
LoC—a new financial loan management system based on smart contracts	Discusses how oracles can be implemented to ensure data privacy in loan management	[134]
A pattern collection for blockchain-based applications	Describes different oracle types and how to recognize the most suitable one according to the needs	[68]
On the characterization of blockchain consensus under incentives	Compares blockchain consensus and oracle consensus under specific incentive mechanisms	[135]
Distributed network slicing management using blockchains in e-health environments	Shows the implementation of a decentralized oracle solution for the management of patient records	[107]
Blockchain for COVID-19: review, opportunities, and a trusted tracking system	Outlines a means to recognize a trusted oracle network for tracking purposes	[101]

To chain or not to chain: a reinforcement learning approach for blockchain-enabled IoT monitoring applications	Presents a blueprint of a private network in which oracle contracts improve their efficiency according to data collected by IoT sensors	[136]
Blockchain as a platform for secure inter-organizational business processes	Discusses oracle data correctness and confidentiality in business process management	[90]

Appendix B. Notable coauthors

Full Name	Institution	Citations	Documents
Zhu, Liming	UNSW, CSIRO-DATA61	612	3
Ingo, Weber	Tu-Berlin	303	5
Jayaraman, Raja	Khalifa University	179	5
Veneris, Andreas	University of Toronto	160	5
Berryhill, Ryan	University of Toronto	147	3
Veira, Neil	SoundHound Toronto	147	3
Muhammad Habib Ur Rehman	Khalifa University	144	3
Davor Svetinovic	Khalifa University	144	3
Ellaham, Samer	Khalifa University	142	3
Yaqoob, Ibrar	Khalifa University	66	4
Ferrari, Elena	University of Insubria	50	3
Weske, Mathias	University of Potsdam	14	3

Appendix C. Complete list of articles sorted by categories.

Oracle Architecture	**Entries**
Beihang University	[1]
CEA LIST Paris-Saclay University	[2], [3]
Eindhoven University of Technology	[4]
ETH Zurich	[5]
Fujian Agriculture and Forest University	[6], [7]
TU-Berlin	[8]
INRS, Montr´eal	[9]
IST Austria	[10]
Jinan University	[11]
Langfang National University	[12]
Macquarie University	[13]
Nirma University	[14]
RMIT University	[15]
Hong Kong University	[16]
University of Canterbury	[17]
University of Dallas	[18]
University of Salamanca	[19]
University of Tartu	[20]

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University of Toronto	[21]
UNSW Sidney CSIRO DATA61	[22]–[26]
Vienna University of Economics and Business	[27]
Jiamusi University	[28]
Sapienza University of Rome	[29]
University of Colorado	[30]
Carnegie Mellon University	[31]
University of Malta	[32]
Politecnico di Milano	[33]
Montana State University	[34]
University of Rijeka	[35]
Oracle Problem	**Entries**
Chiba, Institute of Technology	[36]
EBS University	[37]
IST Austria Klosterneuburg	[38]
John Caroll University	[39], [40]
Khalifa University	[41]
Max Planck Institute	[42]
Montclair state University	[43]
Technical University Munich	[44]
University of Applied Sciences Offenburg	[45]
University of Ljubljana	[46]
University of Verona	[47]–[51]
Imperial College London	[52]
University of Connecticut	[53]
Oracle Proposal	**Entries**
Beijing University of Technology	[54], [55]
Chungnam National University	[56]
Delft University of Technology	[57]
Kleros Cooperative	[58]
Kyushu University	[59]
National Taiwan University	[60]
Sogang University	[61]
Swiss Federal Institute of Technology	[62]
Technische Universit¨at Berlin	[63]
University of Illinois	[64]
University of Toronto	[65]–[68]
Hamburg University of Technology	[69]
South Asian University	[70]
Dublin City University	[71]
South China Normal University	[72]
Rensselaer Polytechnic Institute	[73]
University of Applied Sciences - Kufstein	[74]
Shanghai Jiao Tong University	[75]
Finance	**Entries**

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Aalborg University Copenhagen	[76]
China Merchants Group	[77]
Concordia University Montreal	[78]
Cornell University	[79]
Delhi Technological University	[80]
Khalifa University	[81]
Nanjing University	[82]
NTNU Norway	[83]
Oxford-Hainan Blockchain Research Institute	[84]
SUTD Singapore	[85]
Universit´e Clermont Auvergne	[86]
University of Cagliari	[87], [88]
University of London	[89]
University of Potsdam	[90]
University of Sfax	[91]
University of Houston	[92]
University of Luxembourg	[93]
Beihang University	[94]
University of Verona	[95], [96]
Delft University of Technology	[97]
Artificial Intelligence	**Entries**
Bina Nusantara University	[98]
INRS Montreal	[99]
Khalifa University	[100]
Universidade da Beira Interior	[101]
University of Luxembourg	[102]
University of Toulouse	[103]
Sidi Mohamed Ben Abdellah University	[104]
Business Process Management	**Entries**
KAUST	[105]
University of Insubria	[106], [107]
University of L'Aquila	[108]
University of Postdam	[109], [110]
UEST – China	[111]
Sapienza University of Rome	[112]
Cloud Computing	**Entries**
Khalifa University	[113]
University of Ljubljana	[114], [115]
Université de Montréal	[116]
North Carolina State University	[117]
Data Management	**Entries**
Beijing University	[118], [119]
Chiba Institute of Technology	[120]
Kaunas University of Technology	[121]
Khalifa University	[122]–[124]
Rennes University	[125]

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Shenzhen Technology University	[126]
UNIST - South Korea	[127]
UNSW Sidney CSIRO DATA61	[128]
University of Sherbrooke	[129]
University of California	[130]
Jinan University	[131]
Energy	**Entries**
Technical University of Munich	[132]
Technical University of Cluj-Napoca	[133]
Electric Power Research Institute - Beijing,China	[134]
Healthcare	**Entries**
Khalifa University	[135]–[137]
University of Antwerpen	[138]
Internet of Things	**Entries**
Khalifa University	[139]
National Chi Nan University	[140]
NUDT - China	[141]
Qatar University	[142]
Saint Mary's University	[143]
Technische Universit¨at Berlin	[144]
University of Insubria	[145]
INRS, Montr´eal	[146]
Wayne State University	[147]
University of Oradea	[148]
Blockchain 5.0 OÜ	[149]
University of Sherbrooke	[150]
Supply Chain & Traceability	**Entries**
University of Sherbrooke	[151]
Carlo Cattaneo University	[152]
Khalifa University	[153]
Technische Universit¨at Berlin	[154]
University of Hong Kong	[155]
University of Seville	[156]
University of Verona	[157]
Queensland University of Technology	[158]
Transport	**Entries**
Guangxi University	[159]
National Taiwan University	[160]
Khalifa University	[161]
Fraunhofer FIT & RWTH Aachen University	[162]

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