iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 10 **Issue:** VI **Month of publication:** June 2022

DOI: https://doi.org/10.22214/ijraset.2022.45020

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 10 Issue VI June 2022- Available at www.ijraset.com

Evolution of Smart Contracts- A Bibliometric Analysis and Review

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Abstract: ***Smart contracts are self-executing, deterministic scripts that run transparently on top of a blockchain. They enable trusted transactions and agreements between anonymous parties without the need for a trusted figure or authority. The smart contract code and agreement between the parties are publicly available on the blockchain, making transactions transparent, traceable, and irreversible. Smart contracts have the potential to revolutionize and disrupt numerous industries' traditional operating procedures. Although research on smart contracts has yielded significant results, their full potential remains untapped. A bibliometric analysis was performed in this paper to obtain a holistic overview and to assist academic researchers in developing a comprehensive understanding of the state of scientific research on smart contracts. 513 articles on smart contracts were extracted and analyzed using biblioshiny and VOSviewer from the core collection of the Web of Science (WOS) database. Influential journals, top authors, most contributing countries, and impactful articles in the smart contract domain are revealed. A three-fields plot is constructed to show the interactions between the most relevant sources, author key words, and countries, providing a deeper understanding of the state of global research on smart contracts. Furthermore, keyword co-occurrence analysis identified four clusters representing underlying research streams: (1) smart contracts technology and its applications in healthcare (2) applications of smart contracts in supply chain management (3) smart contracts for the Internet of Things (IOT) (4) Smart contracts for business ventures on consortium blockchains Finally, future research directions are suggested based on areas of low coverage but high potential impact.***

Keywords: bibliometrix, biblioshiny, smart contracts, VOSviewer, Web of Science.

I. INTRODUCTION

Since its inception, Bitcoin has been designed to support complexity beyond currency and payments; the potential for programmable money and contracts was built into the protocol itself [1]. The blockchain technology that underpins the Bitcoin cryptocurrency supports a wide range of transaction types, including escrow transactions, bonded contracts, third-party arbitration, multiparty signatures, and so on [2]. This diversity of transaction types is enabled by smart contracts that
run on top of the blockchain. Smart contracts are self-executing computer programs that run on top of the blockchain when a set of rules is met. The blockchain makes all of the smart contract code and terms public, ensuring transparency and trust. They go beyond the vending machine by proposing to embed contracts in any valuable property that can be controlled digitally. Smart contracts refer to that property in a dynamic, often proactively enforced form, and provide much better observation and verification in situations where proactive measures must fall short [3].

By September 2021, 30.4 million individual smart contracts had been created on Ethereum, compared to only one thousand in September 2015 [4]. The increase in the number of smart contracts between 2015 and 2021 demonstrates the field's relevance and growing interest. The smart contract associated with the Tether project is the most valued smart contract, with a market capitalization of $14.15 billion and nearly 2 million Ethereum accounts holding tokens. There are currently only two bibliometric analyses on the topic of smart contracts: Lennart Ante in [5] used factor analysis for co-citation analysis to identify six different research streams pertaining to technical, social, economic, and legal disciplines; Manzano and Agugliaro in [6] examined smart contract literature extracted from the Scopus database and identified two research streams pertaining to sustainability: power grids and e-commerce. The purpose of this paper is to provide a systematic bibliometric analysis of smart contract literature extracted from the Web of Science (WOS) database, allowing us to gain insight into major contributing countries and journals, trend-setting articles, and promising authors. Key-word co-occurrence analysis is used to identify underlying research streams, and three-field plots are used to draw interrelationships between author keywords, countries, and the most relevant sources.

The paper is organized as follows: The second section provides an overview of data extraction techniques as well as research methodology for descriptive and visual analysis. Section 3 discusses the descriptive bibliometric analysis findings. Section 4 employs keyword co-occurrence network analysis to identify research hotspots in smart contract research. Section 5 concludes with future research directions.

II. DATA SOURCES AND RESEARCH METHODOLOGY

Bibliographic data pertaining to smart contracts was retrieved from the most renowned academic database - Web of Science Core Collection (WOS) which includes four online databases: Social Sciences Citation Index (SSCI), Science Citation Index Expanded (SCI-EX- PANDED), Emerging Sources Citation Index (ESCI) and Arts & Humanities Citation Index (A&HCI). The search term ("smart contract$") was used in the topic field and the results were filtered based on document type(article) and language (English) resulting in 590 articles. After carefully going through the abstracts of these articles 77 articles were excluded and the final bibliographic dataset containing 513 articles was exported in plaintext format.

This article adopts the standard bibliometric analysis process comprising of five steps: study design, data collection, data analysis, data visualization, and interpretation [7] as shown in figure 1.

Bibliometrix (version 3.0), an R-Tool of R-Studio (Version 4.0.2) for comprehensive science mapping analysis, and biblioshiny, the shiny interface providing a web- interface for bibliometrix, were used perform descriptive bibliometric analysis on the metadata from Web of Science [8].Additionally, it was used create a three-fields plot showing the interactions among the most relevant sources, author keywords and countries. VOSviewer (version 1.6.15, http://www.vosviewer.com), a network analysis software tool, was used to construct a keyword co-occurrence network to identify underlying research streams [9].

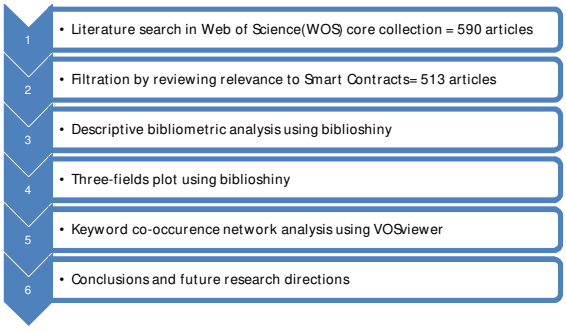

Fig. 1. Research Methodology.

III. RESULTS AND DISCUSSION

A. *Yearly Publication and Growth Trend*

The quantity of publications on a topic is a vital indicator that provides insight into the development trends of scientific research in that field. The citations received by those publications is proportional to the quality of conducted research. Figure 2 presents the cumulative number of articles published and mean citation in a chronological order. The growth in number of publications from 2000 to 2021 can be easily observed from figure. 2016 mark the beginning of the exponential rise in the smart contract research and the highest mean citation of 95.62

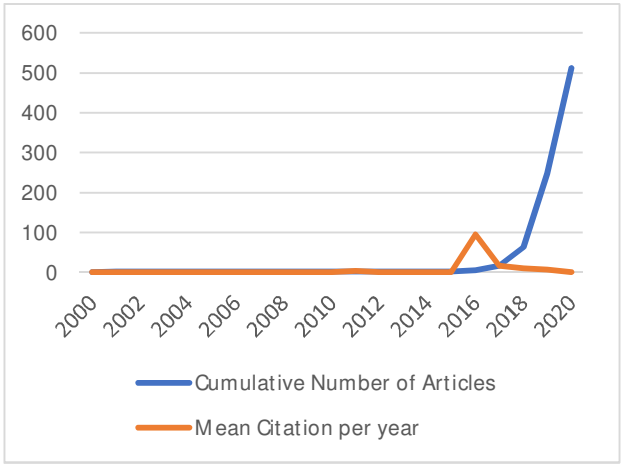

Fig. 2. Yearly publications trends.

B. Core Journals

According to Bradford's Law, there are a few very productive sources, a larger number of sources which give moderate production, and a still larger number of constantly diminishing productivity. The very productive sources make up the nucleus zone which consists of journals particularly de voted to the given subject [10].]. Figure 3 shows the core journals in the smart contract research domain.

Journal	Records	Percent	TLCS	TGCS
IEEE ACCESS	115	22.4	294	1405
SENSORS	31	6	0	197
FGCS	20	3.9	32	140
SUSTAINABILITY	15	2.9	0	51

Fig. 3. Core Journals according to Bradford's Law.

The sample of 513 articles on smart contracts was published in 173 academic outlets. More than one-third of these studies were published in just 4 outlets (see Table 1) which advocates Bradford's law. IEEE Access is the frontier journal with highest level of contribution to the body of knowledge on smart contracts (with TGCS=1405 and TLCS=294). We found out that out of 173 journals, 4 journals come under zone 1. Zone two comprises of 30 journals and zone 3 contains 139 journals.

C. Most prolific authors

In the entire dataset of 1660 authors, 1402 authors (84.5%) have published a single paper related to smart contracts; 184(11.1%) published 2 papers; 47(2.8%) published 3 papers; 27(1.6%) published 4 or more papers. Figure. 4 lists the top 5 contributing authors in the field of smart contracts. Among the top 5 contributing authors, Khaled Salah (Department of Electrical Engineering and Computer Science, Centre for Cyber-Physical Systems, Khalifa University of Science and Technology, Abu Dhabi, UAE) was ranked first in terms of number of publications. He published 11 articles related to smart contracts and has a h-index of 5.

Author	h-index	g-index	m-index	TC	NP	PY_start
SALAH K	5	10	1.667	110	11	2018
CHOO KKR	4	9	1.333	100	9	2018
ZHANG Y	4	9	1	187	9	2017
LI YN	3	7	1	51	8	2018
YU Y	3	6	1	40	8	2018

Fig. 4. Top 5 authors.

With a large number of published high-quality papers, Khaled Salah's influence in the field of smart contracts can be easily observed. As shown in Figure 5(the bubble size is directly proportional to the number of documents published and the colour intensity represents total citations per year), Khaled Salah started to publish articles on smart contracts since 2018, with the greatest number of published documents and highest frequency of average citations per article in 2019.

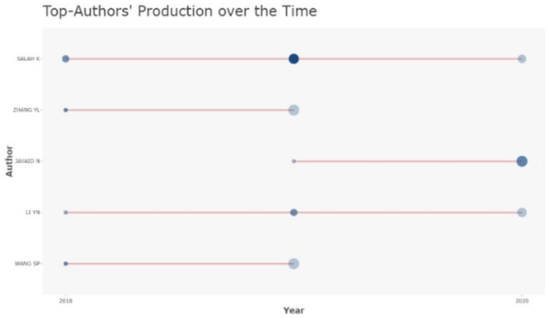

Fig. 5. Top authors production over time.

D. Most impactful articles

This sub-section highlights the top articles in smart contract literature. Fig. 6 lists the top 10 most glob- ally cited articles on smart contracts. "Blockchain and smart contracts for the internet of things" by K. Christidis tops the list with 764 total citations. This paper provides a deep insight into automation of time- consuming workflows usually encountered in an IOT domain. Using smarts contracts significant cost and time savings can be achieved for device interactions. Furthermore, issues pertaining to deployment of an IOT ecosystem through smart contract augmented blockchains are also discussed.

Paper	TC	TC/year
Blockchains and Smart Contracts for the Internet of Things [11]	764	152.8
MeDShare: Trust-Less Medical Data Sharing Among Cloud Service Providers via Blockchain [12]	145	36.25
BlockChain: A Distributed Solution to Automotive Security and Privacy [13]	128	32
Untangling blockchain: A data processing view of blockchain systems [14]	118	39.333
blockchain technology and its relationships to sustainable supply chain management [15]	116	58
Blockchain-Based Scalable and Tamper-Evident Solution for Registering Energy Data [16]	108	36
The IoT electric business model: Using blockchain technology for the internet of things [17]	103	25.75
Healthcare Blockchain System Using Smart Contracts for Secure Automated Remote Patient Monitoring [18]	69	23
Ancile: Privacy-preserving framework for access control and interoperability of electronic health records using blockchain technology [19]	69	23
Industrial IoT in 5G environment towards smart manufacturing [20]	57	19.5

Fig. 6. Most impactful articles.

E. Most productive countries

Fifty-nine countries contributed to the total research output on smart contracts. Figure 7. shows the most productive countries in terms of number of published articles on smart contracts.

As can be observed from Figure 8, China produced the greatest number of documents (504) on smart contracts, followed by USA (143) and UK (74) being the third most productive country.

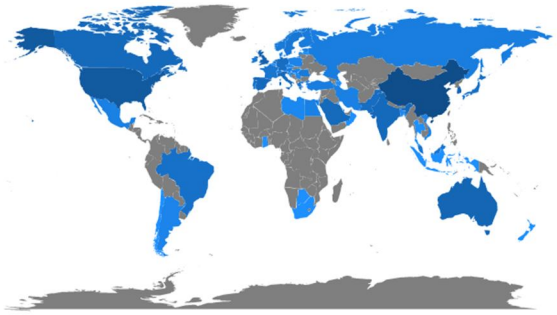

Fig. 7. Countries with highest contribution in field of smart contracts (Number of articles is directly proportional to the color intensity).

F. Three-Field Plot

The interrelationship among research topics, journals and countries can provide useful insights into the research stream. Figure 9 presents a three-fields plot, which shows the interactions among the most relevant sources (left), author keywords (middle) and countries (right) within the smart contract research domain.

Region	Frequency
CHINA	504
USA	143
UK	74
SOUTH KOREA	59
AUSTRALIA	46
CANADA	34
ITALY	34
SAUDI ARABIA	31
SPAIN	29

Fig. 8. Number of articles published by each country.

It can be observed that most studies on smart contracts is published in IEEE Access, the majority of which are authored by Chinese scholars. The highest number of studies on Internet of Things (IOT) are published in the journal Sensors, again with Chinese scholars taking the lead. China, USA and India are leading the research in privacy issues pertaining to smart contracts, most of which is being published in IEEE Access. It is easily observable that china is exceling in the field of smart contract research with its major involvement in every sub domain of the research stream.

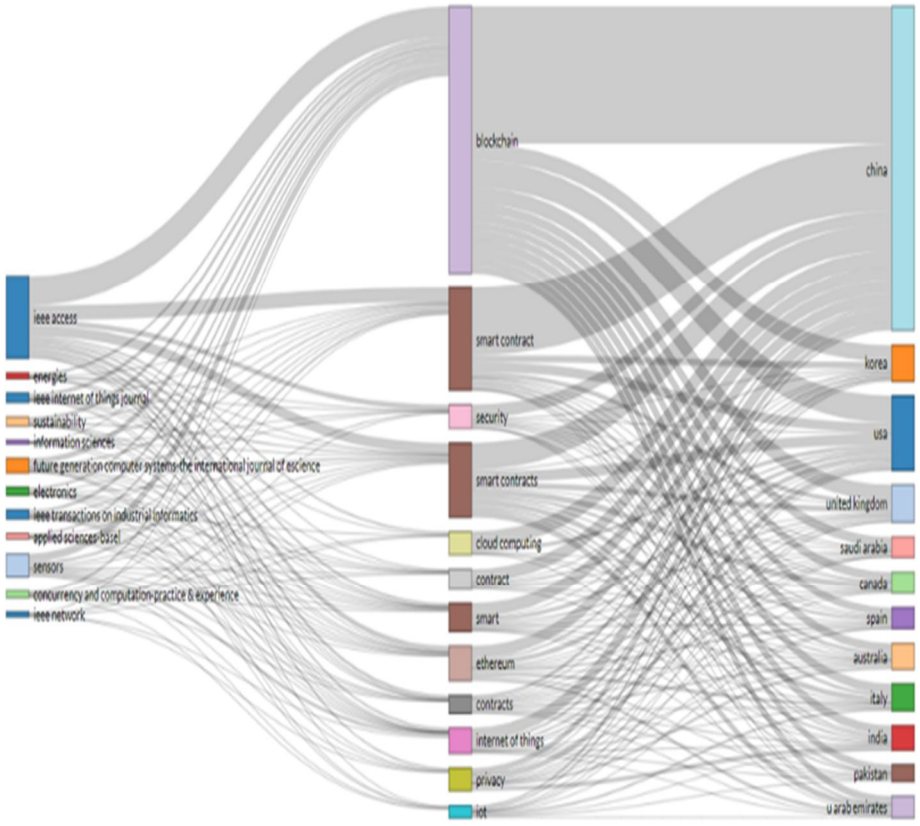

Fig. 9. Three-Field Plot.

IV. KEYWORD CO-OCCURRENCE ANALYSIS

Keyword co-occurrence analysis is used to identify key areas and emerging trends in a research field by measuring the number of times keywords co-occur in pairs in academic articles [21]. Figure presents a keyword co- occurrence network of 75 keywords and 995 links made with VOSviewer. Each node represents a keyword and the size of each node is directly proportional to the frequency of occurrence of that keyword. The most frequent keywords were “blockchain” (n=370), “smart contract” (n=300), “internet” (n=91), “internet of things” (n=76), “security” (n=70), “ethereum” (n=56). We identified 4 clusters of keywords: red, green, blue and yellow. The blue cluster focuses on “blockchain” and “smart contract” with close relationships to “ethereum”, “bitcoin” and “distributed ledger technology”, “healthcare” highlighting the pillars around which the smart contracts are built and the importance smart contract play in healthcare; smart monitoring of patient conditions, drug provenance, transparent and verifiable electronic health records. The red cluster focuses on “technology”, “supply chain management”, “industry 4.0 “, “challenges” and “decentralization” highlighting the role smarts contracts are playing in industrial innovation. Smart contract powered supply chains make the whole process fully transparent and easy to trace the provenance of an object, artifact, etc. The green cluster focuses on “internet”, “internet of things”, “security”, “privacy”, cloud computing” and “access control” highlighting the role smart contracts are playing for research on tackling issues pertaining to Internet of things such as data security, access control, user authentication. Finally, the yellow cluster focuses on “cloud”, “scheme”, “consortium blockchain” and “efficient” which highlights which highlights the importance of consortium blockchains for efficient business ventures which provides a trade-off between transparency and reliability.

V. CONCLUSION AND FUTURE WORK

Smart contracts have already gained a lot of attention from the scientific community but the research is still at its infancy. They possess a lot of potential which is still untapped, ranging from privacy, traceability, security, access control, authentication, decentralization, to name a few. Scientific research has identified numerous fields of applications such as supply chain management, Internet of Things, healthcare, industry 4.0, etc. This paper aims to provide a holistic view of the development in scientific research being conducted on smart contracts from 2000 to 2020. We conducted a bibliometric analysis on scientific literature extracted on smart contracts from the Web of Science (WOS) database. The topic of smart contract has attracted extensive research since the last few years, gaining exponential increase in the number of published articles beginning in 2016. IEEE Access is the leading journal is smart contract research with the highest number of published articles (115) and highest TLCS (294) and highest TGCS (1405). Khaled Salah (Department of Electrical Engineering and Computer Science, Centre for Cyber-Physical Systems, Khalifa University of Science and Technology, Abu Dhabi, UAE) is the most contributing author to this research field with the greatest number of published articles (5), the highest h-index (5) and g-index (10).

"Blockchain and smart contracts for the internet of things" by K. Christidis is the most impactful article on smart contracts which received a total of 764 citations. China tops the list of most productive countries with the highest number of published documents (504) on smart contract research. Three-fields plot of most relevant sources, author keywords and countries reveal IEEE Access published the highest number of articles on smart contracts which are mostly authored by Chinese scholars. Keyword co-occurrence analysis was used to identify research hotspots and emerging research trends. With the help of VOSviewer, we identified four clusters on smart contract research; basic research on blockchain and smart contracts with focus on Ethereum and healthcare, industrial applications of smart contracts ranging from supply chain management to industry 4.0., smarts contracts use cases for the internet of things and lastly smart contracts in consortium blockchains for efficient business ventures. Future research can take place in two directions: researching the hotspot areas already attracting a lot of interest from the scientific community such as smart contracts for IOT, healthcare, industry 4.0, consortium blockchains for business ventures. The second possibility is to research those areas that are not getting enough attention but have the ability to disrupt decades of traditional systems such as decentralized finance (DeFi) [22]. Another promising area for future research is integrity and validity of oracle data that is fed to smart contracts [23]. The results of this study provide academic researchers and field practitioners with a complete overview of the scientific research conducted on the topic of smart contracts which will act as a paved path to get an insight into the research domain and further pursue it.

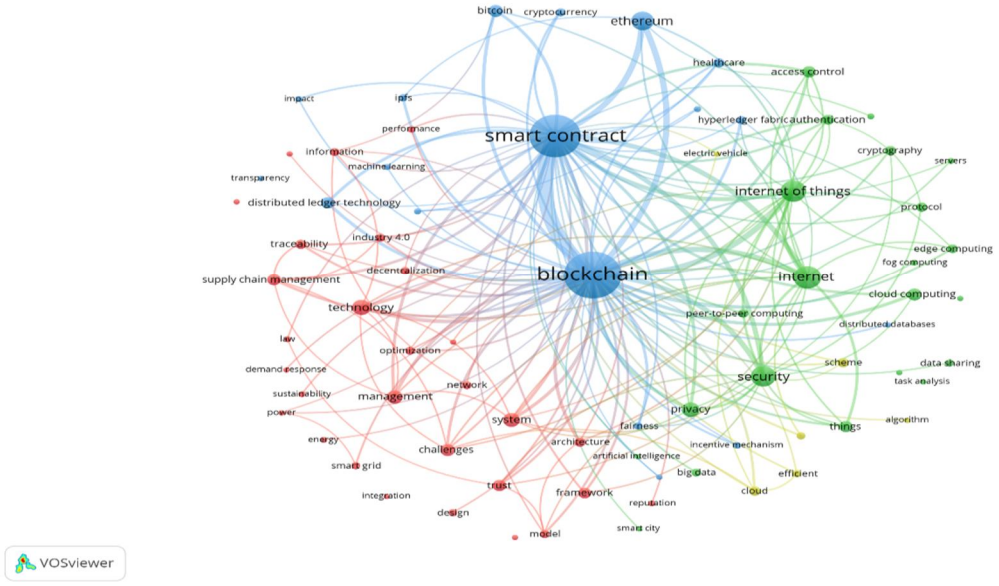

Fig. 10. The keywords co-occurrence network. Minimum number of occurrences of a keyword = 5. Overall, 75 keywords met threshold criteria. There are 4 clusters of keywords: red indicates Cluster 1 (n = 29), green indicates Cluster 2 (n = 22), blue indicates Cluster 3 (n = 18), yellow indicates Cluster 4 (n = 6).

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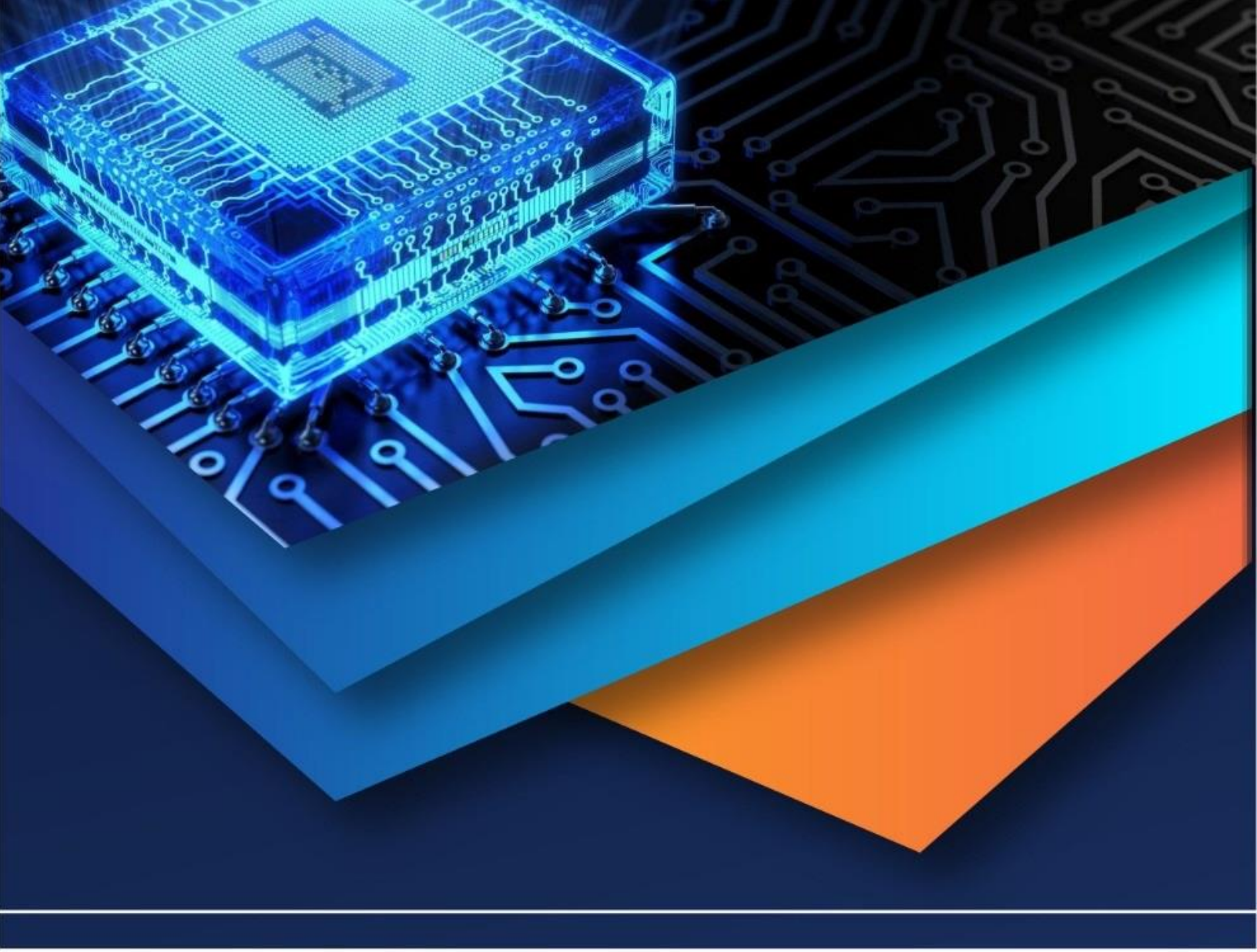

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