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Review

Impact of Proof of Work (PoW)-Based Blockchain Applications on the Environment: A Systematic Review and Research Agenda

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Abstract: Blockchain technology is being looked at to solve numerous real-world problems that demand transparency by meeting sustainable goals. Do we ponder whether this technology is a boon or a bane for the environment? This paper analyses blockchain's dominant consensus method, Proof-of-Work (PoW), which consumes more energy than Malaysia and Sweden and further deteriorates the environment through carbon emissions. This study is the first systematic evaluation of PoW consensus-based blockchain applications' environmental consequences. We found 11 significant Theories, 6 Contexts, and 26 Methodologies (TCM) in 60 reviewed articles. We propose an Antecedents, Drivers, and Outcomes (ADO) model, which depicts that marginal profits drive high energy consumption and carbon emissions, with non-renewable energy proportionally responsible for carbon emissions. The article distinctively uses an integrated TCM-ADO framework for literature synthesis and the PESTLE framework for reporting future research areas. This is the first study to use the following four frameworks: PRISMA; TCM; ADO; and PESTLE for systematic literature review. Profit is identified as one of the most significant drivers of energy consumption and further carbon emissions. The article proposes 65 future research areas and makes theoretical contributions to the literature that may interest academicians, practitioners, and social stakeholders.

Keywords: cryptocurrency; environment; global warming; carbon emission; proof of work; four framework SLR

JEL Classification: O11; O13; O16; 033; Q01; Q56

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1. Introduction

"Bitcoin threatens our existence while blockchain can benefit us" (Truby 2018). "Bitcoin is the first useful implementation of blockchain technology, which can be the primary fuel for the worldwide money transmission network" (Hashemi Joo et al. 2020). However, the way bitcoins are mined severely threatens the environment. The tweet on bitcoin (a PoW-based blockchain application) by US senator Ed. Markey highlights the detrimental impact of such applications on the environment.

> *"When one year of US bitcoin mining creates as many carbon emissions as 7.5 million gas-powered cars—we have a problem. Today's hearing made that even clearer. The crypto industry is growing, but so is the fight for climate justice. We will hold these companies accountable."* —Ed Markey on 7 March 2023[1]

The underlying method of validating a block in bitcoin is known as Proof of Work (PoW). Similar to bitcoin, many other blockchain applications, such as cryptocurrencies, Non-Fungible Tokens (NFTs), Smart Grid, and other green applications, work on this dominant consensus and validation mechanism. The proof of work mechanism requires all the nodes or participants in the network to keep a copy of transactions, which brings transparency—the most important feature of blockchain technology. In other words, the details of a single transaction on the blockchain network are recorded by all the nodes in the network. This recording by all the network participants leads to redundancy in data recording and colossal energy consumption by the electronic devices engaged in the process (Sedlmeir et al. 2020).

Since the most prominent PoW application of blockchain is bitcoin with publicly available data, let us focus on the facts and figures available around bitcoin. According to a study by (Mora et al. 2018), if bitcoin alone's usage grows at the same rate as other widely used technologies[2], it may generate enough CO_2 emissions to raise global temperature past 2 °C in less than three decades. PoW-based bitcoin mining can produce about 90.2 million metric tons of carbon dioxide annually (de Vries 2021). Not only this, but the e-waste disposal also (hardware components) using a conservative methodology (de Vries 2019) can be around 44,400 metric[3] tons per annum (author's calculation) as compared to 16,442 metric tons in 2018 for every 1.5 years of usage. PoW-based bitcoin's annual carbon emissions in 2021 will be accountable for around 19,000 deaths in the future (Truby et al. 2022). Post crypto mining ban in China, Iran picked up in this space by using their non-renewable energy sources to supply power to crypto mining farms which are estimated to release 3530 and 1547 tons of nitrogen oxide and carbon monoxide annually in Iran alone (Talaiekhozani et al. 2021). Out of hundreds of available consensus mechanisms, we chose the PoW because of its energy-intensive nature and dominant use in the blockchain industry. Cryptocurrencies that do not use the PoW consensus protocol use less energy for each transaction (Nguyen and Kim 2018). Unfortunately, the PoW consensus in bitcoin encourages hash rate competition among miners for the opportunity of a block reward, which draws more miners into an arms race and increases the amount of energy used by the entire bitcoin blockchain (Jiang et al. 2021). With global warming and carbon emissions threatening the very existence of humans, this study becomes crucial to evaluate this relationship.

On the positive side, according to supporters, blockchain technology can provide social and environmental benefits that support the UN's Sustainable Development Goals (Adams et al. 2018). There is a growing trend of literature on blockchain applications in the energy sector with future research indications, especially in smart grid or peer-to-peer renewable energy (Wang et al. 2021). Blockchain technology's use in the energy industry is a new area of cross-cutting research that focuses on renewable energy and seeks to offer more effective ways to replace fossil fuels with renewable energy (Wang and Su 2020). Additionally, this technology can contribute to climate protection (Dorfleitner et al. 2021). As per the advocates of blockchain technology, nations that discourage blockchain innovation will miss out on the industry's early days and the rewards that blockchain will eventually provide once it gets established. Numerous traditional sectors, such as healthcare, agriculture, retail, land records, and financial services, that want to improve their business operations in the real world have recently introduced and accepted blockchain technology (van der Waal et al. 2020).

This positive and negative debate reaches a cross-road where we must take cognizance that despite a few countries banning cryptos and other blockchain-based digital assets, these digitally scarce goods will likely be around for a long time. They will bring new ideas to several economic areas, benefiting people. It is essential to separate this bigger picture from the parts (PoW-based blockchain technology) of the digital economy that may be especially bad for the environment and climate (The Whitehouse 2022). In addition, several articles discuss specific issues associated with the growth of the cryptocurrency market, e.g., cybercrime (Corbet et al. 2020) and illegal usage of cryptocurrencies (Foley et al. 2019). While looking for the research gap, we observed that exploring the environmental impacts of PoW-based cryptocurrencies and other applications remains ill-explored and awaits future research (Easley et al. 2019; Li et al. 2019). With this idea in mind, we attempt to quantify and explore the relationship between PoW-based blockchain applications and our natural environment through this study.

Some of the aspects closer to this area have already been covered in the previous systematic literature reviews, including a study by Andoni et al. (2019), which provides a systematic review of blockchain initiatives and efforts in the energy sector. They look at blockchain research projects and startups and use that information to identify the potential and relevant blockchain applications for energy applications. This study, however, is on the positive use cases or research projects, avoiding the academic literature, both on positive and negative dimensions. Another study by Wendl et al. (2023), with the title "The environmental impact of cryptocurrencies using proof of work and proof of stake consensus algorithms: A systematic review," has considered 50 articles from Science Direct and Link springer (two databases). The authors have only focused on cryptocurrencies for review.

Compared to the above reviews, this article makes an original contribution by focusing on the PoW-based applications alone, which is the initial and inherent consensus protocol of blockchain technology (Nakamoto 2008). We have also included four databases: Scopus; Web of Science; Ebsco; and Pro-quest for broader coverage. In addition, an integrated TCM (Theories, Contexts, Methodologies) and ADO (Antecedents, Decisions, Outcomes) framework, along with PESTLE categorization of research areas, makes the methodology, literature synthesis, and reporting rigorous enough to draw meaningful insights, conclusions, and findings. We consider the proposed ADO model and PESTLE-categorized research areas as theoretical contributions in this study. To the best of our knowledge, there is no systematic literature review summarizing the impact of energy-intensive PoW-based blockchain applications on our environment. Given the dearth of literature dealing with the issue of the effects of PoW-based blockchain applications on our natural environment, we propose to collate the academic work performed so far and identify the crucial areas for future research. It will not only help save human lives (emissions accountable for around 19,000 deaths in the future (Truby et al. 2022)) but also pave the way for a sustainable world for future generations.

To understand the dynamics of the relationship between PoW-based blockchain applications and the environment, we start our research journey with some basic intriguing questions in mind. Is the impact positive or negative? Which Applications are more crucial and energy-intensive? Do we need strict policies to address the issues identified? Can this jeopardize our sustainability? We achieve this by answering the following research questions about the relationship between PoW-based blockchain applications and their environmental impact (Figure 1).

Figure 1. Relationship Under Study.

RQ 1: What are the different theoretical lenses and methodologies used to study this relationship? (Using TCM Framework);

RQ 2: What is the nature of the impact (positive or negative) of PoW-based blockchain applications on the environment? (Using context, sub-context, and sentiment identifications);

RQ 3: What are the critical elements and interconnections of this relationship? (Using ADO Framework);

RQ 4: What are the research gaps in the academic literature and potential future research areas? (PESTLE categorization);

The authors aim to find the answers to the above research objectives through a systematic literature review with the possible detrimental effects of blockchain technology on the environment that may endanger the very existence of humans and makes this study significant for policymakers. Additionally, academia should emphasize the urgent need for research addressing crucial sustainability challenges using blockchain technology. The results are also substantial for investors concerned with the ethical and environmental consequences of investing in organizations using blockchain-based applications.

In Section 2, we discuss the background literature, followed by Section 3 on methodology and Section 4 on the literature selection procedure. The descriptive findings and future research are sequentially reported in Sections 5–7. The research procedure is then summarized under the heading discussion in Section 8, followed by a conclusion in Section 9, and a rational discussion of implications in Section 10. Section 11 explains the limitations of this study and the declaration of competing interests, while References part concludes this study with references cited.

2. The Literature Review

This study focuses on the most prominent consensus mechanism of blockchain, PoW, and its interaction with the natural environment. To begin with, we introduce PoW and PoW-based applications (identified in the review process) to the readers, followed by their interaction with the natural environment.

2.1. Proof of Work (PoW)

The PoW protocol was first used by Bitcoin (Nakamoto 2008) and then by Ethereum after a few years (Buterin 2014). In POW consensus, the node that has the right to add the following block to the chain is determined by solving a cryptographic puzzle (technically, a "zero-knowledge proof"), which is a puzzle that is hard to solve but easy to check. "Mining" is a common term for adding a new block, and the nodes that do this work are called miners. Miners who successfully mine a new block are given a certain amount of the native cryptocurrency (or a part of it) as a reward. The nodes are in a race to make the next block. The decision is based only on computer power, not on what makes sense (Zhang and Lee 2020). When a node finishes a block, the information is sent to the other nodes in the network. The nodes check that the block was made correctly and add it to the (block)chain, proving that it fits in with the history of transactions (Bouraga 2021). In practice, it has become exponentially harder to solve the puzzle over time. Now, one needs special hardware (called ASICs or application-specific integrated circuits), a group of computers called "mining pools", and a lot of energy (Küfeoğlu and Özkuran 2019).

2.2. PoW Applications

Out of all the cryptocurrencies (primarily based on PoW), the most prominent is the virtual currency known as bitcoin, which was for the first time introduced to the world in 2008 by an author (or group of authors) going by the anonymous name Satoshi Nakamoto. At the beginning of 2009, the distributed, open, and peer-to-peer bitcoin network went live (Nakamoto 2008). Currently, the scale of cryptocurrency operations is vast, with more than 21,000 cryptocurrencies (Forbes 2022) and a market cap of around US $1 trillion (CoinMarketCap 2022a). The total market capitalization went as high as US $2.83 Trillion in Nov 2021 (CoinMarketCap 2021). Out of the entire crypto-market, Bitcoin and Ethereum, based on PoW, have a combined market share of approximately 60% (CoinMarketCap 2022b). Cocco et al. (2019) highlight that bitcoin, specifically its underlying technology, is a "safe haven" that allows facing modern environmental challenges better than gold. When it comes to the valuation of bitcoin (or any other such crypto), it is determined by three prominent factors—acceptance as a medium of exchange, cost of cryptocurrency mining, and speculative factors (Pakhnenko et al. 2022). With other applications of Ethereum (PoW-based blockchain), the scale of operations of PoW is quite significant since Pow is a blockchain consensus mechanism using enormous energy to validate a block on the blockchain (de Vries 2018).

The next big category of PoW-based applications (refer Figure 2) is non-fungible tokens (NFT). NFTs are the transferable ownership rights to digital assets (such as pictures, music, films, and virtual creations) that are recorded in smart contracts and stored on a blockchain (Dowling 2022). The current market capitalization of NFT is approximately US $2.19 Billion (CoinMarketCap 2022c).

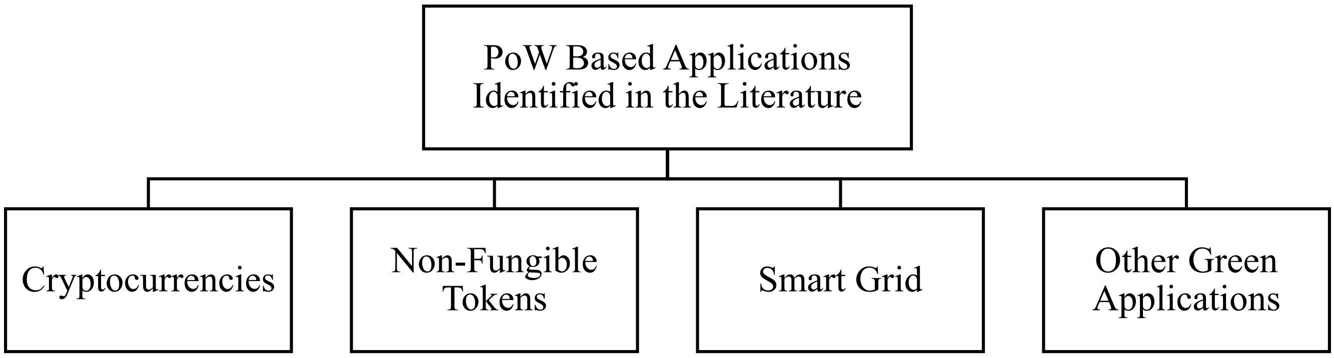

Figure 2. Broad categories of PoW-based applications.

The third category is of smart grid, which is a blockchain-based energy trading idea. The network participants with surplus energy can share the power with energy deficit participants in the blockchain-based smart grids (Park and Kim 2019). The fourth and last category is a miscellaneous category called green applications, with diverse applications working in the direction of sustainability. Under this category, the majority of applications were found in the sectors of renewable energies (61.18%) and general sustainability (28.24%), being either in the planning or starting stages (Dorfleitner et al. 2021). The above categorization is based purely on journal articles reviewed and is not exhaustive.

2.3. Impact on the Environment

The high energy consumption of PoW-based applications is one of the most well-known and problematic aspects of blockchain technology, exceeding the energy consumption of several countries, such as Finland and Belgium. If assumed to be a country, bitcoin alone would have ranked 38th on the most power-consuming countries list. Most bitcoin mining pools are in regions with inexpensive electricity, which generally happens to be the locations with abundant power generation capacity. In some countries/regions, this questionable cheap energy is often sourced from coal or other fossil fuels. The per coin climate damages from bitcoin had been increasing from 2016–2021 rather than decreasing with industry maturation. Even worse, during specific periods, the bitcoin climate damages exceeded the price of each coin created (Jones et al. 2022).

In addition to bitcoin, other cryptocurrencies and applications with similar PoW models also contribute to carbon emissions. Data analysis and testing (Li et al. 2019) proved that the estimated electricity for Monero may consume 645.62 GWh of electricity globally in a single year following the hard split. Since previous studies show that electricity consumption has a direct and positive relationship with CO_2 emissions (de Vries et al. 2022; Goodkind et al. 2020; Howson and de Vries 2022), it may likely contribute to carbon emissions ranging between 19.12 and 19.42 thousand tons per year (Li et al. 2019).

Due to the deliberate energy-intensive design of several blockchain technologies, these applications now seriously jeopardize the global commitment to reduce greenhouse gas emissions (GHGs) under the Paris Agreement (UNFCCC 2015). Additionally, the energy-intensive devices used in PoW consensus require cooling facilities. These validators and miners often opt for data centers in cold climates to avoid needing air conditioning or ventilation (Krause and Tolaymat 2018). This may not need additional energy but certainly contributes to the global warming issue with such a tremendous amount of heat released. Therefore, permanent and strict policies should be applied to reduce energy consumption (Ghosh and Bouri 2022). Furthermore, supporters of PoW-based applications must begin to embrace other greener energy sources, despite being expensive (Fadeyi et al. 2020).

2.4. Social Impact of PoW-Based Applications

On the social side, countries, such as Iran or Russia, could avoid the economic restrictions put in place to improve global security by using bitcoin mining (de Vries 2021). The electrical grid's reliability is impacted by bitcoin mining resulting in power outages, as evidenced by the power disruptions in Tehran and Sukhumi (*Arab News* 2021). Regarding illegal transactions, about 0.3% (in 2020) of the total transaction volume in the network is used by criminals for money laundering and other unlawful activities. In addition, the change in usage patterns may pose a greater threat (Kaul et al. 2021). Moreover, bitcoin has been linked to ransomware used for cyber-extortion and has terrorism links (Lee and Choi 2021). In the context of forced labor, coal mines in Xinjiang power bitcoin mining pools have been highlighted (Zhu et al. 2019).

The advocates of the Degrowth theory highlight that even with the use of renewable energy, the PoW-based applications may be an "energy boomerang effect", which means that measures to improve resource efficiency and decarbonize energy production result in an increase in energy consumption and unsustainable material use throughout the economy (Gunderson et al. 2018). Along similar lines, global per capita carbon emissions and economic growth have a strong bidirectional causal relationship (Li et al. 2021a); therefore, it becomes important to mitigate this carbon emission for economically defined social prosperity. With urbanized countries, such as US and Russia, leading the bitcoin mining, the economic effect of these countries would likely have a diminished effect on carbon emissions (Wang et al. 2022).

3. Methodology

A literature review is required to lay the groundwork for creating a new conceptual model or theory and mapping a selected topic's evolution across time (Kumar 2022). It has been established that the systematic procedures of the literature review reduce bias and offer accurate findings for conclusions (Moher et al. 2009). The academic community has properly acknowledged the value of systematic reviews, and specialized journals and issues exist. Most systematic reviews fall into five categories: domain-based; theory-based; method-based; meta-analytic; and meta-systematic (Paul et al. 2021). We have chosen the domain-based systematic review approach to generate insights.

To identify relevant keywords for database query, we gave a preliminary search on Google Scholar for "blockchain and carbon emissions". The journal and website articles obtained were used to frame the research query pertinent to the selection of the academic literature through four databases used in this study. (refer Figure 3).

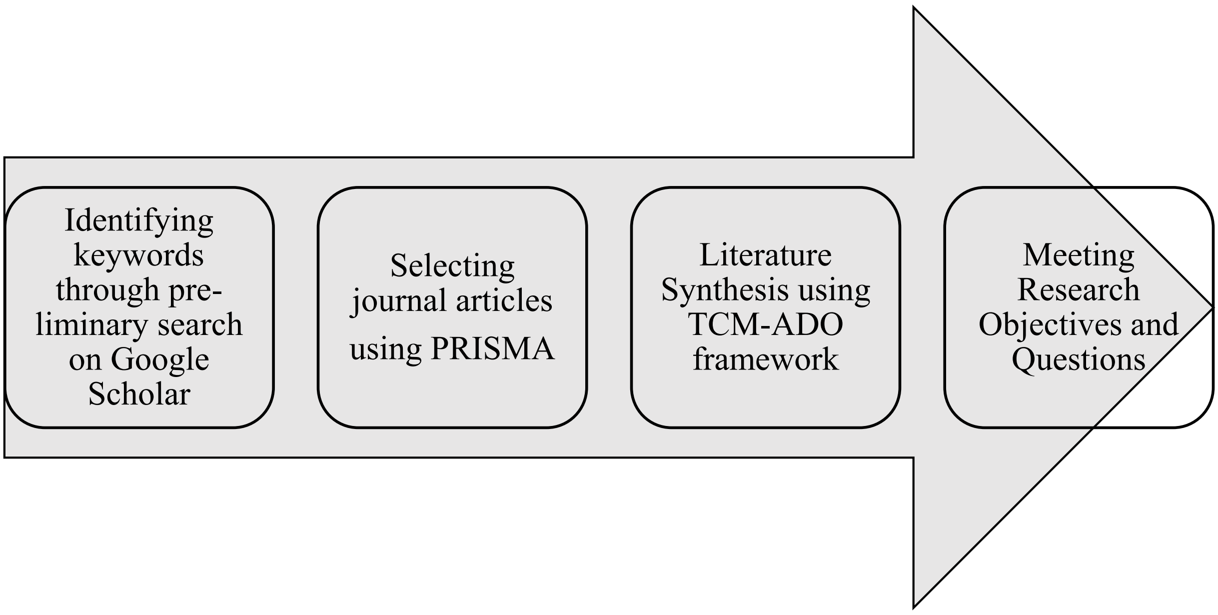

Figure 3. Review Process.

For selecting the relevant literature, this study uses the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) procedure, which includes four steps: identification; screening; eligibility; inclusion (Moher et al. 2009); and additional criteria of adding utmost important cross-referenced articles, commentary, or white paper. The procedure resulted in selecting 59 peer-reviewed articles and one white paper.

For the literature synthesis, we used a domain-based review and a framework-based strategy, where the researcher either uses an existing framework or creates one of their own (Paul and Benito 2018). This study integrates two of the accessible organizing frameworks, ADO (Antecedents, Decisions, and Outcomes) and TCM (Theories, Contexts, and Methods) (Kumar 2022).

To meet the research objective and questions, we used the results obtained after the literature synthesis. In addition to the TCM-ADO framework, which helped us meet RQ1, RQ2, and RQ3, we used the PESTLE framework to contextualize the literature and categorize future research avenues, eventually answering RQ4.

From the methodological point of view, this article uses a rigorous blend of four frameworks for systematic selection (PRISMA), the literature synthesis (TCM-ADO), and the PESTLE for categorizing the relevant research areas for future researchers, practitioners, and other stakeholders.

4. The Literature Identification and Selection (Using Four Stages of PRISMA)

Each stage in the selection of the relevant literature is explained in detail below.

4.1. Identification Stage

We considered four elements in the first stage: keywords; platform; period; and article type. This study began with the identification of search terms. We started with a random search on Google Scholar with the query "blockchain and carbon emissions". Before deciding on the keywords for search in the four targeted databases, the authors went through five articles (Howson 2019; Pan et al. 2019; Al Sadawi et al. 2021; Wang et al. 2020) suggested by Google Scholar and a few websites articles (Carter 2021; Scher 2022) through Google search. The keywords were then finalized and divided into three categories. The first category intended to cover blockchain technology or its dominant application, such as bitcoin or crypto, with the keywords using the "OR" Boolean function ("Blockchain", "Cryptocurrency", "Cryptocurrencies", "Bitcoin"). The second category covered the keywords related to environmental impact using the OR function again ("Environment", "Energy", "Global

Warming", "Carbon"). The final category consists of the blockchain-specific consensus protocol to be studied for this study, i.e., "proof of work", "proof-of-work", "PoW", and "mining". A better explanation is given in Table 1 below:

Table 1. Keyword Search Criteria.

Category 1—Technology	Category 2—Environment	Category 3—Consensus Algorithm
Blockchain	Environment	Proof of Work
Cryptocurrency	Energy	Proof-of-Work
Cryptocurrencies	Global Warming	PoW
Bitcoin	Carbon	Mining

The "OR" Boolean function was used for the keywords within categories, and for between categories "AND" Boolean function was used. The primary platform for the literature search was the Scopus database because it has access to 70% more sources than other databases, such as the Web of Science (Brzezinski 2015). In addition to Scopus, Pro-quest, Ebsco, and Web of Science were also included for broader coverage.

The initial search using the keywords without any filter resulted in 1013 1663, 484, and 380 documents in Scopus, Pro-Quest, Ebsco, and Web of Science Databases, respectively (date—17 January 2023).

4.2. Screening Stage

Post the initial search, we applied the filters to include journals in the source category, in the English language, and finally, in the publication stage, to reach 912 journal publications by 16 January 2023, wherein the starting time frame was not fixed. No discipline filters were applied given that the topic was nascent and for better analyzing the literature around the subject without any discipline constraints. The above query (including filters for Academic journal articles and the English language) resulted in a total of 912 articles, with 371, 162, 72, and 307 articles from the Scopus, Pro-quest, Ebsco, and Web of Science databases, respectively. After removing the 421 duplicate articles, 491 articles qualified for the eligibility stage.

4.3. Eligibility Stage

The eligibility criteria were formulated based on the documents' nature, technicalities, and significance. After the screening, the documents were given a partial text read, emphasizing the abstract, findings, and introduction. The article was dropped from coverage if the title, abstract, and findings were irrelevant. The relevance criteria can be explained with the help of the inclusion and exclusion criteria given in Table 2 below:

Table 2. Inclusion and Exclusion criteria for the review process.

Inclusion	Exclusion
✓ Relationship between PoW-based Blockchain Application and Environment (in the Context of the Natural Environment)	• Publications in the context of the business environment were dropped. • Highly technical papers in a purely technological context were also ignored.

435 articles were found to be irrelevant to the scope of this study leading to their exclusion. In total, 56 articles were finalized for full-text reading.

4.4. Inclusion Stage

The relevant cross-referenced articles (articles cited in the full-text shortlisted journal publications after the eligibility stage) were also considered. Since full-text reading of these 56 documents (finalized in the screening stage) was required to include any cross-referenced articles, the inclusion stage took considerable time. However, it continued with the compilation and synthesis of the literature. Figure 4 elaborates on the PRISMA framework adopted.

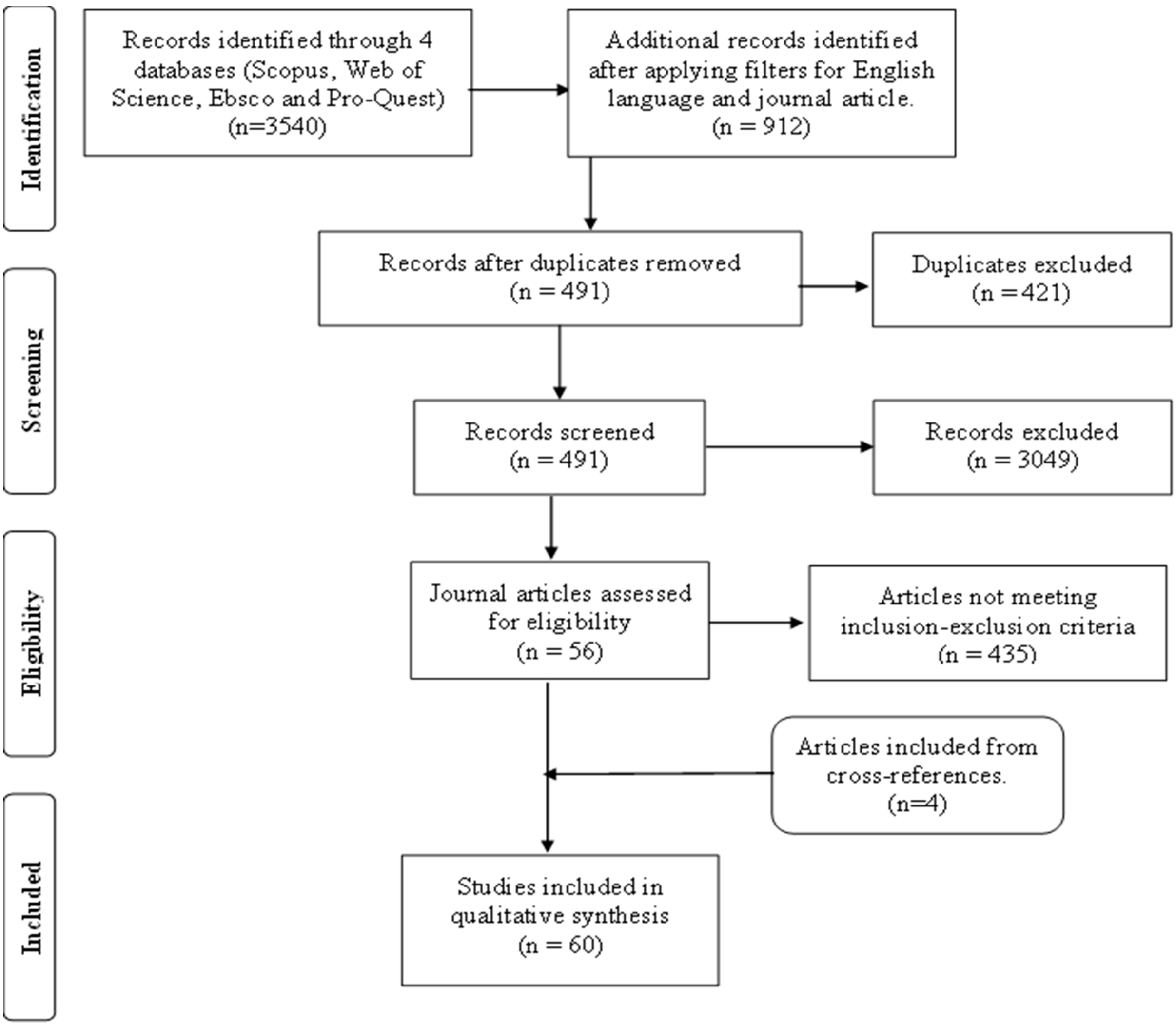

Figure 4. PRISMA approach to review.

5. Descriptive Details of the Documents Reviewed

We have included the descriptive section to provide the bird's eye of the literature analyzed and synthesized in this study. The descriptives that are covered in this part come from publications that were chosen for analysis utilizing the PRISMA Framework. The descriptive does not form part of our novel findings, nor they answer any of our research questions. Given this study's scope, the article selection procedure (PRISMA), and the authors' interpretation of the article's relevance, we believe that the basic information about the progression of the literature, leading authors, publications, countries, and journals reported is accurate.

Figure 5 below depicts the progression of documents published on this topic. The first publication was a review article in 2017 that was themed on "Sustainability of bitcoin and blockchains" by Harald Vranken. Since then, the literature on this topic has been growing but at a slow pace. However, the subject was increasingly getting attention in academic research, with 19 research publications up till 2022 against 15 in 2021.

Table 3 informs about the top five authors in this area, with a leading position taken up by Alex de Vries, a founder of Digiconomist.net, providing an index of bitcoin-based electricity consumption. The other four authors are Christian Stoll, Lena Klaaßen, Ulrich Gallersdörfer, and Peter Howson. All these five authors collectively contribute to 20% of the articles undertaken in this study.

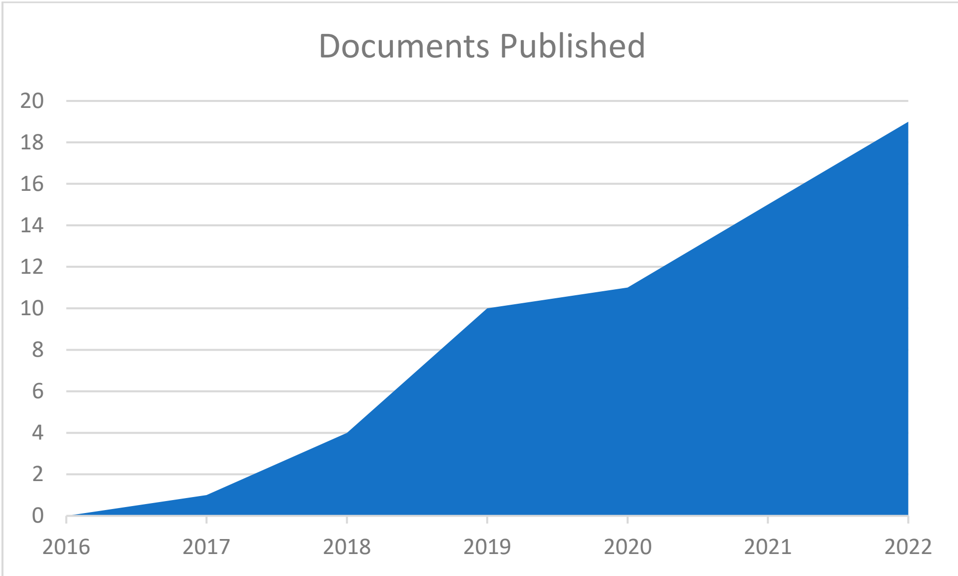

Figure 5. Development of the Literature.

Table 3. Top 5 Authors.

Authors	No. of Documents	Citations	Average Citations per Year
De Vries A	8	401.00	50.13
Stoll C	5	232.00	46.40
Gallersdörfer U	4	203.00	50.75
Klaaßen L	4	203.00	50.75
Howson P	3	54.00	18.00

As per Table 4, the only document with more than 230 citations is a commentary by Alex de Vries in 2018. Review articles by Harald Vranken and Jon Truby titled "Sustainability of bitcoin and blockchains" and "Decarbonising bitcoin: law and policy choices for reducing the energy consumption of blockchain technologies and digital currencies", respectively, are equally important in promoting the research in this area. The peer-reviewed article "The Carbon Footprint of Bitcoin" by Christian Stoll, with more than 120 citations, is also a catalyst for research in this area. Interested researchers and practitioners can read the above top 15 documents to understand the fundamental issues and proponents of research in this critical area.

The USA seems to be the leader in publishing in this area, with seven articles (as per Table 5) fetching 253 citations by 16 January 2023, followed by Germany, China, and the UK with four documents each and 253, 97, and 79 citations, respectively. Interestingly, the most extensive use of PoW-based applications also happens in these four countries. Post-crypto ban in China, the USA has emerged as the most dominant player in PoW-based applications, especially bitcoin mining (Statista 2022). Regarding the importance of documents measured by average citations per document, Germany outperformed all other countries by a considerable margin and scored 51.25 for average citations per document.

The top five journals publishing on the topic under study are enlisted in Table 6 below. The Source *"Energy Research and Social Science"* leads the race with seven articles. It is followed by *"Joule"*, with five peer-reviewed commentaries and one research article. These two journals collectively account for approximately 21% of publications under this study. *"Joule"* outperforms all the journals with 83.50 citations per document, followed by *"Energy Research and Social Science"* with 45.57 citations per document. Most journals are on environmental science and economics, with very few focusing on sustainable finance in this area.

Table 4. Top 15 Documents.

S. No.	Citations	Global Citations	TC per Year
1	de Vries (2018)	235	39.17
2	Vranken (2017)	195	27.86
3	Truby (2018)	157	26.17
4	Stoll et al. (2019)	122	24.40
5	Krause and Tolaymat (2018)	119	19.83
6	Sedlmeir et al. (2020)	114	28.50
7	Jiang et al. (2021)	60	20.00
8	Gallersdörfer et al. (2020)	55	13.75
9	Goodkind et al. (2020)	48	12.00
10	Gourisetti et al. (2020)	47	11.75
11	de Vries (2019)	46	9.20
12	Bouraga (2021)	44	14.67
13	Meynkhard (2019)	43	8.60
14	Howson (2019)	40	8.00
15	Corbet et al. (2021)	38	12.67

Table 5. Top 10 Countries.

Rank	Country	Total Citations	Average Article Citations	Total Frequency	Total Articles
1	Germany	253	63.25	21	4
2	USA	170	24.29	28	7
3	China	97	24.25	26	4
4	UK	79	19.75	13	4
5	Belgium	44	44.00	1	1
6	Netherlands	39	19.50	12	2
7	Italy	25	12.50	8	2
8	Qatar	22	11.00	8	2
9	Czech Republic	18	18.00	3	1
10	Greece	11	11.00	1	1

Table 6. Top 5 Journals.

Sources	Articles	Citations	Avg Citations per Article	Impact Factor
Energy Research and Social Science	7	319	45.57	8.514
Joule	6	501	83.50	46.08
International Journal of Energy Economics and Policy	2	45	22.50	2.95
Sustainability (Switzerland)	2	47	23.50	4.089
Renewable and Sustainable Energy Reviews	2	13	6.50	16.79

6. Findings

This section presents theories used in the literature, contexts, methodologies, and conceptual ADO framework as an outcome of the TCM-ADO framework (Lim et al. 2021; Kumar 2022). The findings are used to answer the research questions raised in the introduction part of this study.

6.1. Theories Used in the Literature

We present the following 11 theories used in 9 different contexts and 12 publications for analyzing the relationship under consideration. The most important theories in the domain are Zero economic theory, MR-MC theory of production, Koomey's Law of computing efficiency, Principal Agent Theory, and Game theory. The use of theories or theoretical lenses to identify the relationship between PoW-based applications and the natural environment is explained in Table 7 below (meeting a part of RQ1).

Table 7. Theories Used in the Literature.

Theories Used	Sub Context in Article	Explanation	Reference
Zero economic profit theory or Perfect competition theory	Estimating Electricity Consumption	The theory was used in the article "Bitcoin boom: What rising prices mean for the network's energy consumption". As per the application of this theory, the mining will continue till it covers the variable cost of production, i.e., till it costs one bitcoin to mine one bitcoin. This study demonstrates that if the price of bitcoin is more than the cost, there is room for adding more computational power to the network.	de Vries (2021)
MR-MC Theory of Economic Production	Estimating Electricity Consumption	The author has considered bitcoin a virtual commodity with a competitive producer's market. The article explains why the need for energy is growing using MR-MC Approach. The Marginal revenue in the case of bitcoin mining is equal to bitcoins received as rewards (Mining rewards and transaction fees) multiplied by the dollar value of bitcoin. Therefore, if the market price of bitcoin is high, the marginal revenue goes up. This high profit leads to an increased gap between MR and MC, leaving room for adding more computational power, i.e., more energy.	de Vries (2018)
Koomey's Law of computing efficiency (doubling every 1.57 years)	E-waste Generation	Koomey's Law describes the efficiency improvements of computing and shows that computations per unit of energy consumed double every 1.57 years. The author used this theory to estimate the e-waste generated in the form of obsolete devices and hardware components.	de Vries and Stoll (2021)
Fama–French Portfolio Theory	Impact of Energy Consumption on Pricing	To understand the bitcoin market, the authors use Fama–French's portfolio analysis theory to understand the market efficiency or inefficiency (Crypto Market in this context). The Fama-French Three Factor model determines the anticipated rate of return on investment based on three factors: total market risk, the extent to which small companies (PoS-based cryptos) outperform large companies (PoW-based cryptos), and the extent to which high-value companies outperform low-value companies.	Sapkota and Grobys (2020)
Principal Agent Theory	Available Policy Choices and Implications	It is used in the context of the government responsible for driving sustainable technological practices. The Principal Agent dilemma occurs when one person (an agent) can make a decision that affects another person. The government can act as an agent by making decisions on behalf of all the stakeholders affected by the emissions caused by PoW-based applications. The article discusses the policy interventions for mitigating the harmful effects of PoW-based applications.	Truby (2018)
Degrowth Theory	Degrowth and Sustainability	The article looks at the PoW-based applications and environment from a degrowth perspective. Degrowth is a 1970s-era radical economic theory. It broadly means shrinking rather than growing economies to use less of the world's dwindling resources. Degrowth supporters claim that it does not involve "living in caves with candlelight" but rather living more simply.	Howson (2021)
Zero economic profit theory or Perfect competition theory	Cryptocurrency Mining and Profitability	The theory was used to evaluate the reduced profitability of bitcoin mining from 2012 to 2016.	Derks et al. (2018)
Theory of Carbon Footprint	Policy Implications on Carbon Emissions	Using the theory of carbon footprint, a theoretical model for bitcoin blockchain carbon emission assessment and policy evaluation is developed. According to the idea, overall carbon emissions are a function of estimated carbon emission flows for a particular region or industry.	Jiang et al. (2021)
Game Theory	Reducing Carbon Footprint	The article argues that Game theory is integral to bitcoin's automated and decentralized network, which is maintained through economic incentives. Bitcoin's game theory framework means that if miners in one place use renewables because it is the cheapest (and most profitable), new miners immediately alter the network's difficulty level and hash power to win new bitcoins. This reaction continues until bitcoin–energy prices balance. The authors have explored the impact of mining on societal damages using the game theory context.	Howson and de Vries (2022)
ESG Theory	Exploring the Impact of ESG Factors	The ESG theory believes that investors should consider the Environmental, Social, and Governance issues or challenges while making investment choices. The entire crypto industry producing Crypto as a financial asset is analyzed using this ESG framework in the given article.	de Vries et al. (2021)

Table 7. *Cont.*

Theories Used	Sub Context in Article	Explanation	Reference
Behavioural Finance Theory	Valuation and Profitability	According to behavioral finance theory, behavior is a leading indicator of risk, and human behavior is primarily irrational and, therefore, unpredictable. This is an important factor in bitcoin (or any other crypto) valuation.	Pakhnenko et al. (2022)
Environmental Kuznets Curve (EKC) theory	Estimating Carbon Footprint	The empirical framework is underpinned by the Environmental Kuznets Curve (EKC) theory (Grossman and Krueger 1991, 1995) in the sense that economic growth (proxied by the development of the cryptocurrency ecosystem) tends to escalate environmental degradation (proxied by CO_2 emissions) before environmental quality can be improved by sustainable economic growth.	Zhang et al. (2023)

6.2. Context of the Literature

(I) Based on Themes

We have segregated the publications into three broad categories (Figure 6), i.e., Positive, Neutral, and Negative, based on the publications' context (not the author's stance in the publication). The document's title, abstract, and, most importantly, findings define whether the context is positive or negative. The authors made the interpretation individually for better reflexivity, followed by a brainstorming session to achieve a consensus about the final reporting. The papers in the positive context broadly focus on four positive contexts—Crypto Mining, Application for sustainable development, Improving consensus mechanism, and Policy interventions.

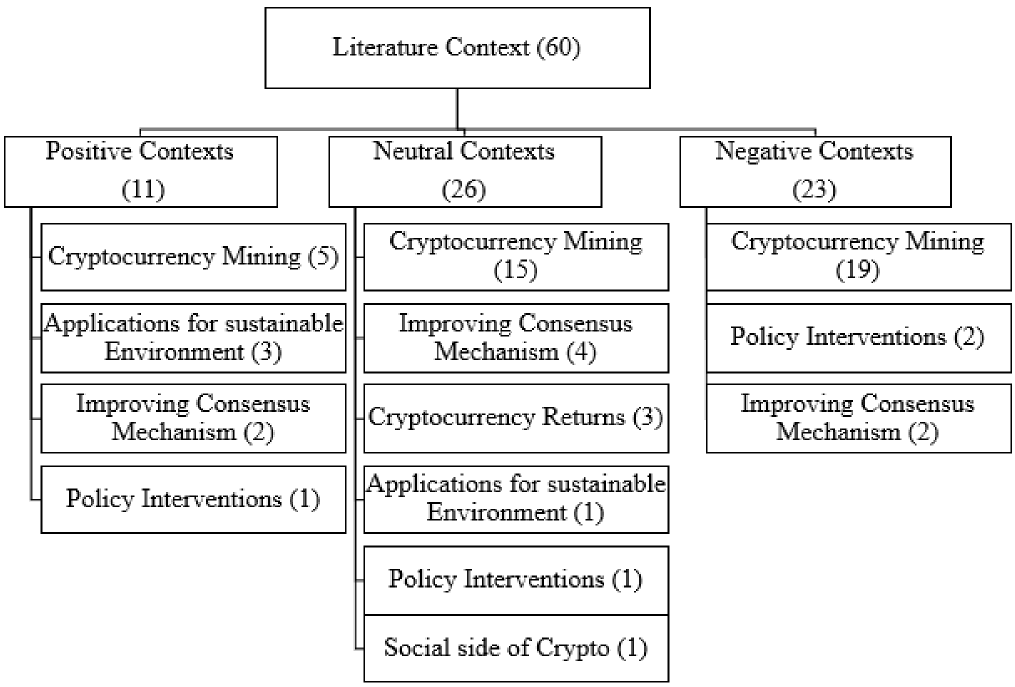

Figure 6. Theme-Based Contextualisation.

On the other hand, most documents focus on the neutral context where two more additions to broad contexts can be found—cryptocurrency returns and the social side of crypto. Finally, the negative literature discusses crypto mining, policy interventions, and improving consensus mechanisms. Further classification of these six contexts into 27 sub-context is given in Table 8.

Table 8. Mapping of Context–Sub context and Authors' Stance.

Contexts (6)	Sub-Context (27)	Documents (60)	The Literature Sentiment		
			Positive (11)	Neutral (26)	Negative (23)
Applications for Sustainable Environment (3)	Mapping the Success of Green Applications	1		Dorfleitner et al. (2021)	
	Improving Efficiency	2	Chen et al. (2022), Park and Kim (2019)		
	Degrowth and Sustainability	1	Howson (2021)		
Cryptocurrency Mining (14)	Estimating Electricity Consumption	8 (1 + 3 + 4)	Vazquez and Crumbley (2022)	Cong et al. (2021), Stoll et al. (2019), Zade et al. (2019)	de Vries (2021), de Vries (2020), de Vries (2018), Gallersdörfer et al. (2020)
	Estimating Carbon Footprint	9 (0 + 2 + 7)		Roeck and Drennen (2022), Krause and Tolaymat (2018)	Calvo-Pardo et al. (2022), de Vries et al. (2022), Zhang et al. (2023), Schinckus (2021), Polemis and Tsionas (2021), Talaiekhozani et al. (2021), Howson and de Vries (2022)
	E-waste Generation	2			de Vries and Stoll (2021), de Vries (2019)
	Economic and Environmental Sustainability	2 (1 + 1 + 0)	Vranken (2017)	Fadeyi et al. (2020)	
	Use of Natural Resources	1			Greenberg and Bugden (2019)
	Carbon Accounting/Allowances	1		di Febo et al. (2021)	
	Climate Change	1		Howson (2019)	
	Cryptodamages in the Form of Air Pollution and Mortality	1			Goodkind et al. (2020)
	Valuation and Profitability	6 (1 + 4 + 1)	Agung et al. (2019)	Pakhnenko et al. (2022), Meiryani et al. (2022), Bejan et al. (2022), Cocco et al. (2019)	Read (2022)
	Estimating Electricity Consumption and Carbon Footprint	2			Sarkodie et al. (2022), Jones et al. (2022)
	Exploring the impact of ESG factors	1			de Vries et al. (2021)
	Impact of POW on Energy Consumption.	2	Islam et al. (2022), Ghosh and Bouri (2022)		
	Estimating the Network's Computational Power	1		Küfeoğlu and Özkuran (2019)	
	Optimizing Electricity Transmission	1		Bondarev (2020)	

Table 8. *Cont.*

Contexts (6)	**Sub-Context (27)**	**Documents (60)**	**The Literature Sentiment**		
			Positive (11)	Neutral (26)	Negative (23)
Cryptocurrency Returns (3)	Profitability	3	Agung et al. (2019)	Corbet et al. (2021), Derks et al. (2018)	
	Connectedness among PoW and PoS-based Cryptocurrency	1		Milunovich (2022)	
	Cointegration between Price and Cost	1		Kristoufek (2020)	
Improving Consensus Mechanism (2)	New Consensus Proposed	5 (1 + 2 + 2)	Saad et al. (2021)	Philippopoulos et al. (2020), Qiu et al. (2022)	Li et al. (2020), Lasla et al. (2022)
	Factors for Selecting a Blockchain or Consensus	3 (1 + 2 + 0)	Sedlmeir et al. (2020)	Bouraga (2021), Gourisetti et al. (2020)	
Policy Interventions (4)	Policy Implications on Carbon Emissions	1			Jiang et al. (2021)
	Carbon Accounting	1		Gallersdörfer et al. (2021)	
	Intervention Options to Make NFTs Sustainable	1			Truby et al. (2022)
	Available Policy Choices and Implications	1		Truby (2018)	
The social side of Crypto (1)	Regional Development	1		Meynkhard (2019)	

Note: The context of the article may be negative, but the author may have taken a positive, neutral, or negative stance while evaluating the problem under the said article.

(II) Sentiment-based categorization.

Apart from looking at the literature from positive, negative, and neutral contexts, we also have analyzed the stance/sentiment of the author by categorizing them into positive, negative, and neutral stances or sentiments. The details of the author's stance/sentiment are given in Table 8.

(III) Based on Perspective

We have also categorized the documents under study from the PESTLE perspective. The most dominant perspective taken by the authors is that of the environment, accounting for about 26 publications out of 60. The environmental perspective is followed by the economic, technological, social, political, and legal perspectives with 14, 9, 5, 5, and 1 research publication (refer to Figure 7 for PESTLE classification of the academic literature under study). There is a vast scope for future research by looking at the said relationship from a political, legal, and social perspective. Therefore, the same PESTLE classification is used to describe the future research areas in segment 6 of this study.

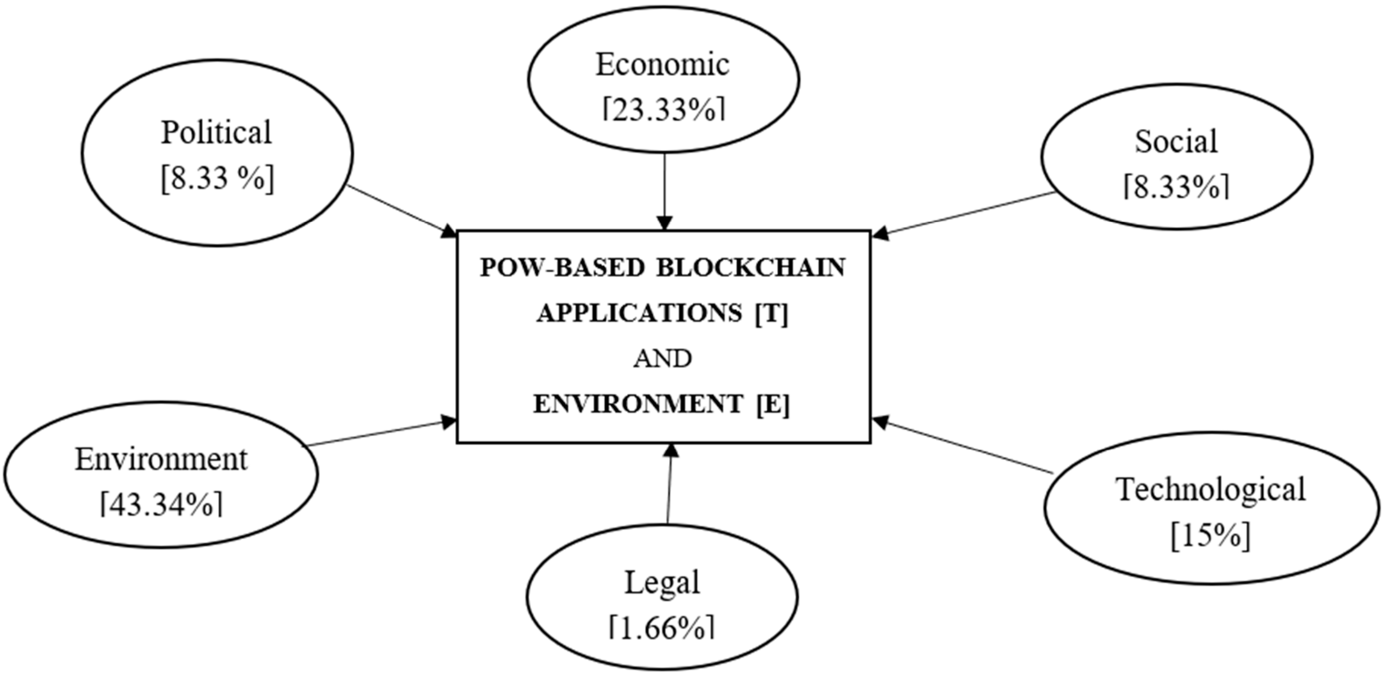

Figure 7. PESTLE perspective-based contextualization.

6.3. Methodologies Used in the Literature

From the methodological point of view, the documents can be bifurcated into broad categories—conceptual and empirical. The further categorization of conceptual papers is performed based on the context and sub-context in which these methods were used. For empirical papers, the broad methodology and different sub-tool categorizations are used. The review revealed that empirical articles had used econometric tools, such as OLS, Cointegration and VECM, DCC-GARCH, Logit Regression, MVMQ-CAViaR model and Granger causality, FIGARCH and MFDFA for 12 publications out of 26 (approx. 46%). It is followed by empirical modeling with nine publications. Qualitative methods, such as case studies and interviews are hardly used to assess this relationship. Table 9 further elaborates on this.

Table 9. Methods adopted in the literature.

Methodological Overview				
Nature	No. of Documents	Broad Context/Methodology	Document Sub-Division	Refined Context/Methodological tool
Conceptual	34	Applications for a Sustainable Environment	3	Smart Grid, Sustainability, and Energy Trading
		Cryptocurrency Mining	20	Majorly covering estimation models for energy, carbon emission, air pollution, mortality, climate change, Valuation, and Profitability.
		Improving Consensus Mechanism	8	New Consensus Proposed (N = 5) and Consensus Selection (N = 3)
		Policy Interventions	3	Carbon Accounting and Policy Selection, including policies for NFT.
Empirical	26	Case Study	2	Region (Chelan County, Washington) and Electricity Company (Greenidge LLC)
		Econometric Tool	12	OLS Regression (2), Cointegration and VECM, DCC-GARCH, Logit Regression, MVMQ-CAViaR model and Granger causality, FIGARCH and MFDFA, and VAR and Cumulative Impulse Response, Artificial Neural Network (ANN)
		Experiment	1	Lab Experiment
		Interviews	1	Interview + Modelling (MM)
		Machine Learning Tool	1	Feedforward Neural Networks (Deep Learning)
		Modeling	9	The Literature-based (5) and Regression-based (2)

6.4. Conceptual ADO Model (Model Specific to Bitcoin Product)

After reviewing all the publications, it was determined that the literature focuses mainly on the following dimensions (refer to Table 10):

Table 10. Conceptualization of ADO framework.

Context	Sub Context	Antecedents	Drivers	Outcomes	Reference
Cryptocurrency Mining	Estimating Electricity Consumption	Bitcoin Price Increase (decrease)	MR-MC increases	High (Low) Energy Consumption	de Vries (2021)
Cryptocurrency Mining	Estimating Electricity Consumption	Max Positive MR-MC	Purchase of Bitcoin Miner Device	More Energy Consumption	de Vries (2018)
Cryptocurrency Mining	E-waste Generation	EE (Energy Efficiency of the Device in J/TH) > BE (Energy Efficiency of the Network in J/TH)	The Usage of the Device Becomes Unprofitable	Generation of E-waste as soon as the Device Becomes Unprofitable (Specially ASIC Devices)	de Vries and Stoll (2021)
Cryptocurrency Mining	Impact of Energy Consumption on Pricing	Trust in the Application by Stakeholders	Marginal Profit/ Returns	Energy Consumption	Sapkota and Grobys (2020)
Policy Interventions	Policy Intervention Options to make NFTs Sustainable	Impact on Climate Change and Mortality	Design Side Interventions (PoW), Industry-Focused Policy Interventions, Energy Consumption-Focused Interventions, Tax Measures	Reduced Carbon Emissions	Truby et al. (2022)
Cryptocurrency Mining	Crypto Damages in the Form of Air Pollution and Mortality	Energy Consumption and Carbon Emission from Crypto Mining	Crypto-Damage 1 CO_2 Emissions Converted to Air Pollution (Using US Federal SCC),	Crypto-Damage 2 Human Exposure to Emissions Converted to Mortality (Using Exposure Response Function)	Goodkind et al. (2020)
Policy Interventions	Policy Implications on Carbon Emissions	Carbon Taxation	Tax Payment for Carbon Emission Generated Affecting MR-MC (Profitability)	No Curbing of Emissions as long as Mining is Profitable	Jiang et al. (2021)
Improving Consensus Mechanism	Factors for Selecting a Blockchain or Consensus	Need for Data Security	Redundancy in Recording Transactions	High-Energy Consumption	Sedlmeir et al. (2020)

Antecedents: Variables, such as Bitcoin Price, Energy Efficiency of Hardware Devices (EEd), Carbon taxation, Trust, and Need for Data Security, impact the Marginal Profit of a miner in a PoW consensus mechanism;

Decisions/Drivers: Marginal profit, purchase and sale of hardware equipment, the Hash rate in the network, and redundancy in recording transactions are the four drivers that lead to energy consumption and, in turn, would lead to carbon emissions, air pollution, mortality, and policy interventions of political, technological, and legal nature;

Outcomes: The outcome is seen as an impact on energy consumption leading to carbon emissions moderated by the proportion of non-renewable sources used in validating and maintaining the PoW-based consensus mechanism. The carbon emission then gives rise to other related issues such as global warming, air pollution, and mortality.

The marginal profit is a crucial driver in determining the energy consumed. As long as the mining is profitable, the miners will keep adding more computational power to the network by purchasing more hardware equipment (de Vries 2021). The list of antecedents affecting the marginal profit includes bitcoin price (de Vries 2021), the energy efficiency of the device used in mining (de Vries and Stoll 2021), trust in PoW-based blockchain application by the stakeholders (Sapkota and Grobys 2020), and carbon taxation (Jiang et al. 2021) [Refer Figure 8]. Furthermore, data security requires recording a transaction or data on as many nodes as possible, leading to redundancy in recording transactions (Sedlmeir et al. 2020). Recording on such a large scale requires more expense leading to a reduction in marginal profit. Additionally, global prices for energy sector commodities, especially crude oil and natural gas, positively affect the bitcoin price movement (Meiryani et al. 2022). The high correlation between bitcoin prices and bitcoin energy consumption is also validated by (Bejan et al. 2022).

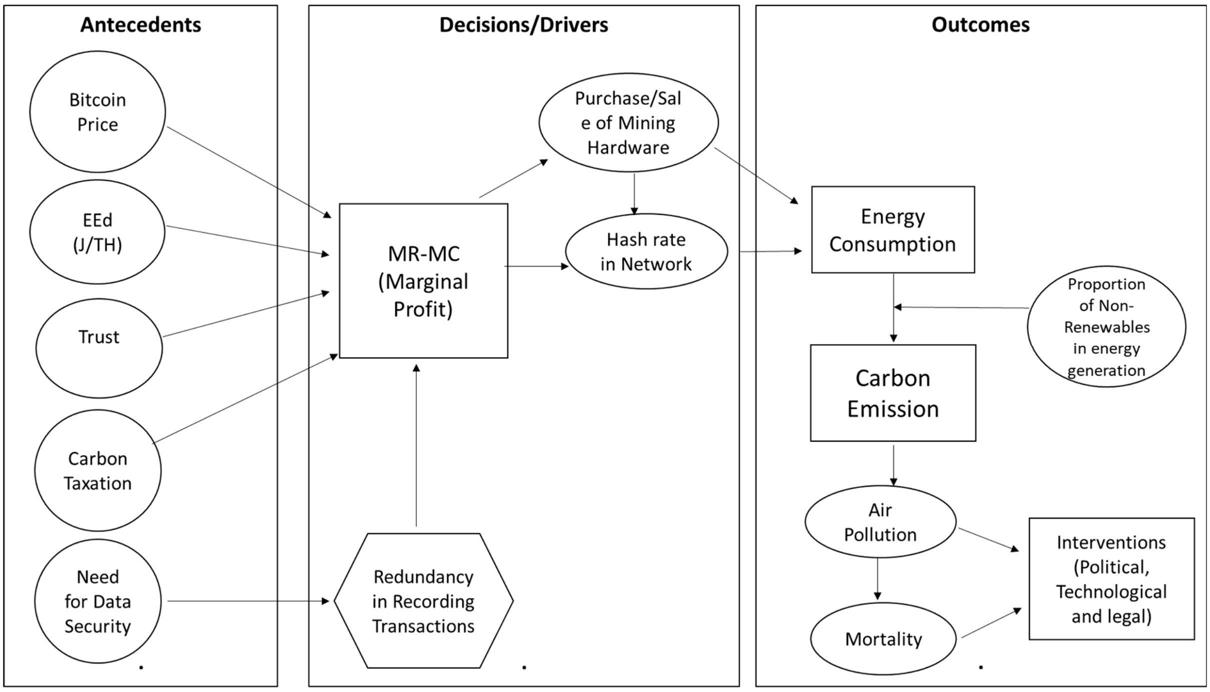

Figure 8. Proposed ADO Model.

Regarding drivers in the process, marginal profit paves the way for adding more computational power using hardware equipment and an increased hash rate in the network. This increased hash rate and the addition of new hardware equipment results in high energy consumption (de Vries 2021). The higher the miner's bitcoin revenues, the more gradual the effect on environmental degradation (Polemis and Tsionas 2021).

The carbon emissions are, therefore, dependent on the energy consumed in this process to the extent of using non-renewable sources in energy production for such consumption. These carbon emissions are, in turn, responsible for air pollution and human mortalities (Goodkind et al. 2020), due to which it becomes crucial to resort to policy interventions (Truby et al. 2022).

7. Future Research Areas (PESTLE Perspective)

The future research areas around the relationship in this study are categorized into PESTLE areas for better clarity for the academicians and practitioners interested in this study (Eierle et al. 2022; Flegr and Schmidt 2022). Traditionally, PESTLE has been used as a tool to evaluate the external environmental factors of a firm. The significant benefits of the PESTLE framework are its adaptability and capacity to simplify the examination of complicated external factors (Peattie 1999). Instead of a firm, we analyze the external environmental factors of blockchain as an industry. Therefore, the framework is a good fit, assuming the decentralized blockchain industry is a unit for analyzing external environmental factors. After reading around 18 documents, the authors felt that the literature had political (Ghosh and Bouri 2022), economic (Agung et al. 2019; Milunovich 2022), social (Greenberg and Bugden 2019; Howson and de Vries 2022), technological (Gourisetti et al. 2020; Philippopoulos et al. 2020), legal (Jiang et al. 2021) and environmental (Bondarev 2020; de Vries and Stoll 2021; Howson 2019) perspectives. PESTLE is a widely used technique in academic publications; for example, the developing ecological literature employs the PESTLE framework to evaluate a CO_2 reduction process from multiple perspectives (Fozer et al. 2017) and to assess the causes of green behaviors in a systematic manner (Li et al. 2021b). Therefore, the authors decided to look at the relationship under study using the PESTLE framework, which might help readers get a broader picture of PoW-based applications and their impact on the environment. Furthermore, using terms, such as policy interventions, government efforts, and emission regulations, demonstrates that the document addresses a political aspect.

Similarly, terms, such as earnings, returns, and cost of production, represented the publication's economic perspective, while terms, such as mortality and community exposure, reflected its social perspective. Documents concentrating on technological considerations included phrases, such as enhancing consensus and consensus innovation. The paper having a legal viewpoint was identified by terms, such as industry regulation in a particular region and local norms, among others. In addition, the dominant environmental perspective utilized terms, such as e-waste, energy consumption, and air pollution. The identification of the PESTLE topic focused primarily on the document's central theme, majorly covered in the title, abstract, and findings sections of the documents analyzed.

7.1. Political

i. Will renewable energy solve blockchain technology's emission and e-waste problem?
ii. What options other than transitory measures can be adopted?
iii. Which policy intervention measures are most effective in mitigating the harmful effects of BT on the environment?
iv. Is Crypto a currency or commodity—comparison of definitions by different countries?
v. Is there a possibility of adopting cryptocurrency as the world's dominant currency for inter-country transactions with countries looking to challenge the dominance of the dollar?
vi. What kind of taxation measures would be most effective for mitigating or reducing carbon emissions from PoW-based applications?
vii. What is the difference between the energy consumption of ASIC-resistant and Non-ASIC-resistant PoW applications? Can an ASIC-resistant policy help?

viii. Universal policy solutions (non-geographical) can be explored to limit carbon emissions and promote the blockchain industry;
ix. Exploring the Cost Benefit Analysis of the blockchain-based smart grid;
x. The blockchain and environmental relationship can be studied from a Degrowth perspective, which is an entirely different field of research.

7.2. Economic

i. Framework for Accounting for Carbon Emissions can be conceptualized for PoW applications other than bitcoin (Gallersdörfer et al. 2021);
ii. Different cryptos and their relationships can be explored with consensus-based categorization—energy-intensive vs. fewer energy cryptos. One such study (Milunovich 2022) analyses the connectedness of PoW-based and PoS-based cryptocurrencies;
iii. The presence of cointegration between cryptocurrency (other than bitcoin), price, and cost can be tested using weekly or monthly data (Kristoufek 2020).
iv. The cost and final-price relationship can be explored using different regression techniques and the frequency of data sets;
v. The impact of PoW-based applications' energy consumption on traditional and renewable energy companies can be explored (Corbet et al. 2021);
vi. The question of how to make mineable cryptocurrencies more sustainable can be explored;
vii. With cryptocurrencies developing to possess a very similar ability to that of long-standing traditional financial assets and attracting a large number of investors (Kyriazis et al. 2023), the energy consumption or Carbon Footprint of different cryptos can be estimated and compared;
viii. The different consensus mechanisms can be compared by taking a portfolio perspective (for example, Sapkota and Grobys (2020) take three consensus algorithms into account);
ix. Empirical studies can determine whether the crypto markets are efficient or inefficient;
x. Reasons for higher returns in cryptos with Hybrid consensus compared to POS/PoW-based cryptos can be identified or explored;
xi. Future research can explore the role of mining pools (energy side explored in (Cong et al. 2021)) on carbon emissions, air pollution, and mortality;
xii. The profitability of bitcoin from a broad industrial viewpoint is lacking, but it can be examined by quantifying the cost of environmental factors;
xiii. It is possible to understand the profitability of multiple cryptocurrencies by using qualitative approaches that expose the various costs (unavailable in the public domain) associated with the mining process;
xiv. Different new algorithms can be tested for lesser energy consumption using Proof of Concept or sidechain (Agung et al. 2019).
xv. The profitability of the new consensus mechanism can be tested and compared with PoW or any other dominant consensus mechanism;
xvi. How market price affects block difficulty and, in turn, energy consumption?
xvii. The progression of the crypto industry and the cost of its climate damage in dollars/other currencies can be estimated (Jones et al. 2022).

7.3. Social

i. The amount of electricity used to mine cryptocurrencies in a given place or region may be explored using different mining regions as a case study;
ii. Documentation and empirical estimations for the locations of mining hotspots, the variation in an area in terms of emissions causing localized pollution, and the affected people may be explored;
iii. The extent of crypto damages (air pollution and mortality) with different VSLs (value of statistical life) in other countries can be explored. Debates regarding

different VSLs for different regions must be encouraged in the literature (Goodkind et al. 2020).

iv. Community response (using a case study approach) of different countries where such crypto boomtowns exist can be captured, which could differ in the context of ethnicity, level of development, gender proportion, IT exposure, sources of energy, such as coal, natural gas, etc. (Greenberg and Bugden 2019);

v. The impact of such high energy consumption of PoW-based applications on society through social indicators (GDP per capita, HDI, etc.) can be studied (Meynkhard 2019).

vi. The progress and effectiveness of the crypto climate accord, voluntarily set up in April 2021 by UN high-level climate champions, can be traced;

vii. The actual/potential impact of voluntary measures, such as the Crypto Climate Accord and carbon offsetting measures, can be explored (Howson and de Vries 2022);

viii. Measures by different countries and the UN, such as banning and tax measures to disincentivize PoW-based applications, can be identified, collated, and discussed;

ix. Exploring the impact of bitcoin mining/NFT/other PoW applications on the social (e.g., work practices, equality, and health effects) and governance (opaque mining practices, power concentration, adverse indirect economic impact, and tax evasion problems) factors (de Vries et al. 2021).

7.4. Technological

i. Less energy-intensive consensus methods are being developed, but a more energy-intensive solution that can solve real-world problems can be explored. For example-(Chen et al. 2022) solve practical optimization problems instead of meaningless maths puzzles;

ii. How energy efficient is the reputation-based consensus using Ethereum, Cordano, etc., sidechain applications? (Qiu et al. 2022)

iii. Future research can examine consensus mechanisms for establishing categories based on shared features. Such categorization can assist blockchain investors in choosing a consensus approach. For example, Bouraga (2021) uses 28 blockchain consensus protocols to make four categories;

iv. The study of smart grid applications of blockchain technology from an economic and business perspective can result in revolutionary green sustainable practices (Park and Kim 2019);

v. The proposed consensuses, such as E-PoS (Extended Proof of Stake), DIPS (Difficulty-based Incentives for Problem-Solving), Green-PoW, and Robust PoS, can be tested for their energy efficiency and decentralization (Saad et al. 2021; Lasla et al. 2022; Li et al. 2020);

vi. The Blockchain Architecture Framework (BAF) proposed by Gourisetti et al. (2020), which is a consensus selection guide for investors in blockchain technology, can be made more robust by incorporating more consensus mechanisms;

vii. Adoption of BAF can be tested using case study methodology, i.e., suggesting appropriate consensus on a case-to-case basis.

7.5. Legal

i. For reducing energy consumption and carbon emissions, legislative policies and practices of different countries could be analyzed (especially the US, which has become a leader in the crypto mining post-ban in China);

ii. What legal solutions can reduce energy consumption and mitigate carbon emissions?

7.6. Environment

i. Quantifying the impact of switching from PoW to PoS, as targeted by Ethereum, using robust assumptions can help in the estimation of reduction in energy consumption and further carbon emissions. For example, Islam et al. (2022) estimate a saving of 99% from PoW and PoS, but the estimation process suffers from many limitations and excessive assumptions;
ii. Relationship between energy consumption and new hardware added;
iii. The relation between network size and the average price of electricity can be explored;
iv. Despite many research articles, estimating past energy consumption and forecasting future energy consumption is a crucial area of research. However, since the majority of articles focus on bitcoin (de Vries 2018; Küfeoğlu and Özkuran 2019; Stoll et al. 2019; Sarkodie et al. 2022) as a PoW-based blockchain application, other applications, such as NFT, altcoins and non-financial applications using the PoW are largely ignored;
v. Similar to energy consumption, the estimation and forecasting of carbon footprint is another vital area defining the trajectory of blockchain as a technology from the environmental perspective. Unfortunately, most of these estimations are restricted to bitcoin (Calvo-Pardo et al. 2022; Roeck and Drennen 2022; Sarkodie and Owusu 2022; Calvo-Pardo et al. 2022), ignoring the other PoW-based applications;
vi. New methods can be created to better assess the amount of e-waste generated annually;
vii. An e-waste estimation model similar to de Vries and Stoll's (2021) and Roeck and Drennen's (2022) can be used for assessing other cryptocurrencies;
viii. The role of ASIC (Application-Specific Integrated Circuit) devices in e-waste generation can be explored;
ix. The relationship between new, improved devices and e-waste generation can be explored;
x. Other than POW, the impact of different algorithms on e-waste can be explored;
xi. The researchers may explore the effectiveness of blockchain-based green applications for climate protection. For example, Dorfleitner et al. (2021) map the performance of 85 such applications. A more extensive data set can make the results more robust. A case study method taking individual applications to evaluate their success can provide reliable results;
xii. Future research may include understanding the impact of carbon allowances on the prices of cryptocurrencies other than bitcoin (di Febo et al. 2021) or even NFT. These prices would eventually affect energy consumption;
xiii. How cooling equipment affects the overall power consumption of Bitcoin, Ethereum, or other PoW-based blockchain applications?
xiv. Future research might benefit from a better understanding of the energy requirements for crypto-mining operations and maintenance, labor expenses, electronic trash production, and other intrinsic costs;
xv. Krause and Tolaymat (2018) compare energy consumption by mining traditional metals vs. mining cryptocurrencies. As a result, more comprehensive and robust comparisons can be made to better evaluate the opportunity cost of diverting energy to cryptocurrencies (a non-essential product);
xvi. It has been seen that most China-based crypto miners shifted to Kazakhstan[4] (after the crypto ban in China), i.e., from hydropower in China to non-renewable powered countries such as Iran and Kazakhstan, leading to an increase in carbon footprint. Therefore, the impact of the ban on PoW-based applications in a specific county (such as bitcoin in China) on the carbon footprint can be analyzed;
xvii. The relationship between redundancy in recording transactions on PoW-based blockchains and energy consumption can be explored;

xviii. Further centralized transaction recording can be compared with the latest blockchain consensus mechanism for energy consumption;

xix. Quantile heterogeneous autoregressive models and quantile coherency can be used to link cryptocurrency energy usage to climate change;

xx. The scenario-based examination can measure the dynamic relationship between cryptocurrency technology and climate change. Moreover, it would be fascinating to see if decentralized financial instruments have more environmental advantages than traditional ones (Zhang et al. 2023).

The political and legal side of the issue is not explored in much detail, probably because of the decentralized nature of PoW-based blockchain applications. The issue needs attention through a collective agreement of all countries for effective policy interventions, as in the case of global warming, terrorism, or tax evasion issues. The social side of this study is highly nascent and calls for case study methodology and other qualitative methods to analyze the social impact of PoW-based applications.

8. Discussion

We started by reading five research articles on Google Scholar and some website articles using a basic Google search query for "Blockchain and Carbon Emission". This basic inquiry helped us to frame a suitable query for the four databases, including comprehensive ones, such as Scopus and WoS. From the four databases, we finalized 56 documents for our study after going through all four stages of PRISMA—Identification, Screening, Eligibility, and Inclusion. Four more documents were added using cross-references, including one white paper. Given the nascent literature in this area, we chose journal documents, including commentaries and short surveys, for our study. For the analysis of the selected papers, the integrated TCM-ADO framework was chosen along with the PESTLE framework for the identification of the context of the literature and areas for future research. This article identifies crucial areas, important journals, authors, documents, and countries publishing on the relationship under consideration. Furthermore, prominent theories, contexts, methodologies, antecedents, decisions, and outcomes are explored within the boundaries of the selected literature for analysis in this paper. After proposing the ADO model and explaining the interlinkages between various components of this relationship, this study ends with the identification of future research areas using the PESTLE framework. Sections 6.1–6.3 of this article help us meet RQ1, while Section 6.2 help us meet RQ2. The RQ3 and RQ4 are answered by Sections 6.4 and 7, respectively.

9. Conclusions

This article provides a thorough understanding of the literature on the environmental impact of PoW-based applications. Based on the inclusion and exclusion criteria, the authors analyzed and summarized the pertinent literature and proposed a conceptual framework and future directions for research. This study addressed the four research questions. To answer the first question, 11 theories are used predominantly in 6 contexts and 27 sub-contexts with econometric tools and conceptual models as principal methodologies (Sections 6.1–6.3). To answer the second research question, we identified the positive and negative nature of impact in the form of positive and negative contexts and the sub-context of the literature studied. Most studies focus on negative contexts, including cryptocurrency and PoW-based mining, cryptocurrency returns, the need for improving consensus mechanisms, and policy actions required to mitigate the harmful impact on the environment. Positive research topics discuss sustainable and social development (Section 6.2 (I)). The ADO model in Figure 8 answers the third question by explaining all critical elements of the relationship under study and its interlinkages. Marginal profit is the central driver leading to high energy consumption and further carbon emissions moderated by the proportion of non-renewable energy sources used in the process. Finally, this study addresses the fourth research question by providing future research areas and analyzing the relationship under study using the PESTLE (political, economic, social, technological, legal, and environmental) (Section 7).

The results of this study recommend immediate attention from the policy-makers to make blockchain applications less power-intensive and more sustainable. There is a scope for underpinning many existing theories while performing research using conceptual as well as empirical methodology. The literature on this topic is dominated by negative context, and very few articles talk about the positive role of PoW application on our natural environment. The articles are dominated by conceptual, which is a pattern likely to prevail for the next few years since blockchain is itself dynamic and in the nascent stage of adoption. The literature predominantly focuses on bitcoin, which is the most popular application of PoW-based blockchain. The ADO model (Figure 8) highlights the critical factors (antecedents and drivers) leading to bitcoin-specific energy consumption, pollution, and mortality (outcomes). The model suggests the profit vs. environment trade-off where the miners are choosing profits. Since the technology is not regulated per se, the environment is likely to suffer in the absence of regulations, guidelines, and legal frameworks. We finally conclude by identifying 65 possible research areas categorized into political, economic, social, technological, legal, and environmental (PESTLE) perspectives. This PESTLE categorization is likely to behave as a catalyst in advancing the research in a holistic way, with something in store for researchers interested in these six PESTLE categories.

To conclude, it would be fascinating to investigate the issues and benefits of blockchain technology concerning the environment, which may or may not be universal because the applications of such new technologies always involve challenges and trade-offs (Howson 2021). Blockchain's auditable and decentralized transaction features offer a creative way to build trust mechanisms, which can be advantageous and innovative for industrial development and remote transactions. However, soon, the global attempt to limit GHG and carbon emissions may be hampered by the high GHG emission behavior of the bitcoin blockchain. The trade-off should therefore be explored and researched further in the future. Before implementing this potential technology across several businesses, we must consider the trade-offs carefully. Future models must be created without reliance on energy usage and their disproportionate negative impact on society because the underlying technology is expected to stay and can offer considerable benefits.

10. Implications

10.1. Theoretical Implications

From the theoretical perspective, the findings of this study are relevant to advance the academic literature around sustainable technologies. It will be helpful for the researchers in identifying crucial concerns, constraints, and opportunities that need urgent attention from academicians for theory-building and strategic policy-making for the successful and sustainable implementation of blockchain technology in various fields. This work could be used as a reference for collectively using four different frameworks—PRISMA, TCM, ADO, and PESTLE—to enhance the rigor of the literature reviews. The 65 proposed future research opportunities would help in building a sound foundation for the topic under this study.

10.2. Practical Implications

The current study is critical for practitioners looking at blockchain technology to solve problems requiring trust and immutability. With an increasing focus on sustainable operations and investment, it is recommended to include the insights from this article before considering the selection of a consensus mechanism and making a cost-benefit analysis of implementing blockchain as a technology. The practitioners can look at the ADO model to analyze the impact of antecedents on marginal profit, which could be a primary goal for investors especially.

10.3. Social Implications

Identification of sustainability threats and opportunities through this study can serve to reassess the allocation of scarce resources (being used by PoW application), resulting in a significant contribution to society dealing with detrimental challenges, such as global warming, air pollution, and environmental degradation. This study highlights the need for the immediate attention of the policymakers on PoW-based blockchain applications for meeting sustainable development goals (SDG) and mitigating the harmful impact on the environment.

11. Limitations of this Study

The scope of this study has been limited to journal documents in the final stage of publication and the English language. The article in the press, conference proceedings, various industry reports, and other such sources are kept out of the purview of this study. The selection of 56 from the 491 papers, apart from 4 cross-referenced, is based on relevance identified from the title, abstract, and keywords. There is a possibility of omitting a few relevant documents that the search query could have missed. Additionally, there is a possibility that certain research gaps get addressed by researchers by the time this article is available for readers. The authors claim the results and reporting to be true, given 17 January 2023 as the cut-off date, and the scope is limited to the keywords used for the literature selection.

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Notes

1. Senator Ed Markey (D-Massachusetts) chaired a session of the Committee on Environment and Public Works on 7 March 2023, focusing on the energy usage of mining. He tweeted it right after this session. The post is publicly available on the twitter platform.
2. Comparative analysis was performed using the 40 different technologies for which data are easily accessible. Cars, cable TV, cell phones, central heating, colour TV, computers, credit cards, dishwashers, disc brakes, dryers, e-readers, electric power, electric range/burners, electronic ignition, adoption of Real Time Gross Settlement, smartphones, and social media are a few of them.
3. 44,400 metric tons = 66,600 metric tons/1.5 years. [66,600 = 0.3 (Weight/hash rate) * 222 Exahash rates (hash rate of bitcoin per second)] Source—Table 1: Renewable Energy will not solve bitcoin's sustainability problem.
4. Source: https://www.reuters.com/technology/chinas-ban-forces-some-bitcoin-miners-flee-overseas-others-sell-out-2021-06-25/ (accessed on 16 January 2023).

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