

Legal Approaches to Addressing the Environmental Impact of Blockchain Technology

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Abstract

Blockchain technology, particularly through its proof-of-work consensus mechanism, has become a cornerstone of decentralized applications like cryptocurrencies, supply chain management, and finance. However, concerns over its environmental impact—specifically, its significant energy consumption and carbon footprint—have emerged as a critical challenge. This review explores the environmental implications of blockchain, focusing on energy-intensive mining processes and the associated carbon emissions. The article examines existing international and national legal frameworks aimed at addressing global environmental concerns, such as the Paris Agreement and regional efforts like the EU Green Deal, and evaluates their effectiveness in regulating blockchain's ecological footprint. The review highlights key legal strategies to mitigate blockchain's environmental impact, including carbon offsetting programs, energy efficiency regulations, and incentives for greener consensus mechanisms. Furthermore, it addresses challenges and controversies surrounding the regulation of blockchain, particularly the conflict between rapid technological development and slow-moving legal frameworks. The article proposes future directions for mitigating blockchain's environmental footprint, emphasizing the need for stronger international cooperation and innovative legal strategies that balance technological advancement with sustainability. Finally, the paper offers recommendations for policymakers to integrate environmental considerations into blockchain regulation while encouraging collaboration between the blockchain industry and environmental organizations. By exploring these legal approaches, the review provides insights into how blockchain can evolve in an environmentally sustainable manner, contributing to global sustainability goals without sacrificing innovation.

Keywords: Blockchain technology, Environmental impact, Energy consumption, Carbon emissions, Legal frameworks, Sustainability.

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1. Introduction

Blockchain technology, initially introduced as the underlying framework for cryptocurrencies, has rapidly evolved into a transformative force with applications spanning finance, supply chains, healthcare, and beyond. At its core, blockchain enables secure, decentralized transactions without the need for intermediaries, offering promising innovations in various sectors. In finance, it facilitates the operation of cryptocurrencies like Bitcoin, allowing peer-to-peer transactions without reliance on central banks. In supply chains, blockchain enhances transparency, enabling the traceability of goods from origin to consumer.

The healthcare industry is also exploring blockchain for secure patient records and efficient data sharing across institutions. However, as blockchain adoption grows, so too do concerns about its environmental impact, particularly the energy-intensive nature of blockchain mining. The process of verifying transactions, especially in proof-of-work (PoW) systems, has been widely criticized for its substantial energy consumption and its contribution to carbon emissions.

The environmental concerns associated with blockchain technology are particularly acute in the case of PoW-based networks, where the validation of transactions and the creation of new blocks require extensive computational power. This computational effort translates into massive energy usage, as mining operations typically rely on power-hungry hardware that requires constant energy input to maintain operations. The global adoption of blockchain, especially for digital currencies like Bitcoin, has led to an escalation in the demand for electricity, raising alarms about its long-term sustainability. This energy consumption, which is often sourced from non-renewable energy sources, further exacerbates the growing climate crisis. In addition to the direct environmental impact of energy consumption, blockchain's carbon footprint is also influenced by the type of energy used, the location of mining operations, and the reliance on high-powered computers that contribute to electronic waste.

The purpose of this review is to critically examine the legal frameworks currently in place or under development to mitigate the environmental impact of blockchain technology. The paper will explore how national and international legal mechanisms can be used to regulate or incentivize more sustainable practices within the blockchain industry. Specifically, it will focus on existing regulatory approaches, propose potential legal solutions, and highlight the challenges inherent in balancing technological innovation with environmental protection. The scope of the paper will encompass an analysis of the energy consumption associated with blockchain mining, the global efforts to reduce carbon emissions, and the adoption of alternative consensus mechanisms that might offer more environmentally friendly solutions. Additionally, it will address the broader environmental concerns, including the lifecycle impact of blockchain hardware.

This review will proceed in the following sections: first, it will provide an overview of the environmental impact of blockchain technology, focusing on energy consumption, carbon emissions, and the environmental challenges posed by mining. The paper will then explore current international and national legal frameworks addressing these concerns, highlighting both successes and gaps in regulation. Following that, the discussion will turn to potential legal strategies for mitigating the environmental footprint of blockchain, including carbon offsetting, energy efficiency standards, and incentives for greener alternatives. The review will conclude by examining the challenges of regulating blockchain's environmental impact, offering recommendations for policymakers, and considering the role of innovation in shaping a more sustainable blockchain ecosystem.

2. The Environmental Impact of Blockchain Technology

The environmental impact of blockchain technology is primarily driven by the energy-intensive process of transaction validation, which is central to blockchain's decentralized nature. In PoW systems like Bitcoin, miners use vast amounts of computational power to solve complex cryptographic puzzles in order to validate transactions and create new blocks. This process requires the use of specialized hardware, such as ASICs (Application-Specific Integrated Circuits), which are designed to optimize mining efficiency. These devices, while highly effective in mining operations, consume enormous amounts of electricity. For example, it is estimated that Bitcoin mining alone consumes more energy annually than some countries (Mora et al., 2018). The widespread adoption of cryptocurrencies and other blockchain applications has only amplified the energy demands associated with blockchain networks, creating significant concerns about the sustainability of such systems in the face of growing global energy needs.

The energy consumption associated with blockchain is not only a technical issue but also an environmental one. The majority of blockchain mining operations are powered by electricity derived from non-renewable sources, including coal and natural gas. This reliance on fossil fuels contributes to the carbon footprint of blockchain networks, further exacerbating the global climate crisis. Studies have shown that Bitcoin mining, for instance, results in millions of tons of carbon dioxide emissions annually, contributing to the overall increase in greenhouse gas emissions worldwide (Stoll et al., 2019). The environmental burden is particularly pronounced in regions where electricity grids are predominantly powered by coal-fired power plants, amplifying the ecological consequences of blockchain operations. Furthermore, the geographic distribution of mining

operations can create disparities in environmental impact, with areas relying on cleaner energy sources experiencing a lower carbon footprint compared to those dependent on fossil fuels.

In response to these concerns, alternative consensus mechanisms have been proposed as more energy-efficient alternatives to PoW. One such mechanism is proof-of-stake (PoS), which reduces the need for computational power by relying on validators who stake their cryptocurrency holdings as collateral to validate transactions. Unlike PoW, where miners compete to solve cryptographic puzzles, PoS participants are selected to validate transactions based on the amount of cryptocurrency they have staked, significantly reducing energy consumption. Ethereum, the second-largest cryptocurrency by market capitalization, has already transitioned to a PoS-based system, known as Ethereum 2.0, in an effort to reduce its environmental impact (Buterin, 2021). Other blockchain platforms are exploring similar alternatives, highlighting the potential for greener consensus mechanisms that could mitigate the environmental concerns associated with blockchain technology. However, these alternatives are still in the early stages of development and have not yet been fully adopted across the blockchain industry.

Beyond energy consumption and carbon emissions, blockchain technology also raises concerns related to electronic waste (e-waste). The hardware used in blockchain mining, such as specialized ASICs and GPUs (Graphics Processing Units), has a limited lifespan and is frequently replaced by more powerful and efficient models. This constant upgrading of mining equipment contributes to the growing problem of e-waste, as discarded devices end up in landfills, posing environmental and health risks due to the toxic substances they contain. Additionally, the rapid pace of technological advancements in the blockchain industry means that mining equipment becomes obsolete at an accelerated rate, exacerbating the issue of e-waste and further straining waste management systems. Although some initiatives have been proposed to recycle mining hardware, the scale of the problem remains significant, and the environmental impact of e-waste from blockchain mining is an often overlooked but crucial aspect of the technology's overall ecological footprint.

In conclusion, while blockchain technology holds tremendous potential for revolutionizing various industries, its environmental impact cannot be ignored. The energy consumption associated with PoW-based systems, the carbon emissions resulting from fossil fuel reliance, the exploration of alternative consensus mechanisms, and the broader environmental concerns related to e-waste all highlight the need for effective regulatory frameworks. Without a concerted effort to address these issues, the long-term sustainability of blockchain technology could be compromised, making it essential for policymakers and industry leaders to collaborate on developing solutions that balance technological innovation with environmental responsibility.

3. International Legal Frameworks for Environmental Protection

International environmental law has evolved significantly in recent decades to address the growing global concern about climate change and environmental degradation. Key agreements such as the Paris Agreement have set ambitious global targets for reducing carbon emissions and limiting the rise in global temperatures. Under the Paris Agreement, nearly every country in the world has committed to implementing national measures aimed at reducing greenhouse gas emissions, with a long-term goal of limiting global warming to well below 2°C above pre-industrial levels. These commitments are primarily focused on energy transition, deforestation, industrial emissions, and other major environmental factors, but blockchain's energy consumption remains an issue that is not directly addressed in this framework. The Paris Agreement calls for stronger efforts from both developed and developing countries to reduce emissions, but its focus is on industries such as energy production, transportation, and manufacturing, not on emerging technologies like blockchain (UNFCCC, 2015).

Another significant international initiative is the European Union's Green Deal, which aims to make Europe the world's first climate-neutral continent by 2050. The European Union's legislative framework seeks to address carbon emissions through regulations that target sectors such as transportation, energy, and agriculture, while also promoting renewable energy and energy efficiency. The EU has been at the forefront of creating policies to regulate the digital economy, including the digital asset sector, with initiatives such as the Digital Services Act and the Digital Markets Act. However, the environmental impact of blockchain technology is not specifically covered by the EU Green Deal, although there are efforts underway to integrate more sustainable practices into the European digital economy. As blockchain becomes more integral to various sectors, it is expected that the EU will refine its regulatory frameworks to encompass emerging technologies and address their environmental footprints (European Commission, 2019).

While the Paris Agreement and the EU Green Deal are critical international instruments aimed at mitigating environmental harm, they do not fully address the specific challenges posed by blockchain technology. Blockchain's high energy consumption and carbon emissions remain outside the direct scope of these agreements, which focus on broader environmental concerns. International laws and agreements on environmental protection, therefore, often fail to address the unique and sector-specific environmental impacts of emerging technologies like blockchain. The regulatory gaps in current international frameworks are significant, particularly in terms of providing direct guidelines or incentives to reduce the environmental harm caused by blockchain's energy consumption. While some general environmental regulations, such as carbon pricing or energy efficiency standards, could apply to blockchain mining operations, a dedicated legal framework is required to directly tackle its environmental implications.

In response to these gaps, global cooperation is essential. Addressing the environmental impact of blockchain requires countries to collaborate through international organizations and treaties to create a more cohesive and comprehensive regulatory environment. Blockchain's decentralized nature, which operates across borders, presents challenges for any single nation to regulate effectively on its own. Therefore, international cooperation is vital for developing standards, setting energy efficiency requirements, and coordinating carbon reduction efforts. Global entities like the United Nations, the World Bank, and the International Energy Agency could play a critical role in facilitating discussions and agreements on how to manage the environmental impact of emerging technologies, including blockchain. A multilateral approach to blockchain's environmental regulation could enable countries to share knowledge, technology, and best practices to reduce the sector's carbon footprint while still allowing for innovation and technological growth.

4. National Legal Approaches to Blockchain's Environmental Impact

As blockchain technology continues to grow in prominence, national governments have begun to explore ways to regulate its environmental impact. Various jurisdictions have implemented, or are considering, policies to mitigate the carbon footprint associated with blockchain mining and to incentivize the adoption of more sustainable practices within the industry.

The European Union, which has long been a leader in climate action, is actively addressing the environmental impact of emerging technologies, including blockchain. The EU Taxonomy for Sustainable Activities, which categorizes economic activities based on their environmental sustainability, does not explicitly include blockchain mining. However, the EU is in the process of developing a more comprehensive regulatory framework for digital assets, which could potentially include environmental considerations. The European Commission's proposed Digital Finance Package, for instance, seeks to create a clear legal framework for digital financial services, including cryptocurrency markets. At the same time, the EU is encouraging greater transparency and sustainability in its digital economy, and it is likely that future regulations will address the environmental impact of blockchain, particularly as the technology becomes more embedded in finance and other sectors. Additionally, the EU Green Deal's broader climate targets and energy regulations are expected to influence the adoption of greener technologies within the blockchain industry (European Commission, 2020).

In the United States, the regulatory landscape for blockchain's environmental impact varies significantly from state to state, as federal oversight has been limited. New York, for example, has taken a significant step in addressing the energy concerns of blockchain mining with its cryptocurrency mining moratorium, which imposes a temporary halt on new cryptocurrency mining operations powered by fossil fuels. This moratorium is part of New York's broader efforts to reduce its carbon emissions and transition to more sustainable energy sources. Other states, such as Texas, have become hotspots for cryptocurrency mining due to their cheap electricity prices, although there are growing concerns about the long-term environmental sustainability of these operations. At the federal level, the U.S. government has been slow to implement comprehensive regulations that would address the environmental impact of blockchain mining, but the Biden administration's climate agenda could lead to greater scrutiny of high-energy industries, including blockchain. In particular, the administration's push for decarbonization could eventually extend to the cryptocurrency sector, especially as the environmental impact of blockchain becomes more widely recognized (U.S. White House, 2021).

In China, the government has taken a much more aggressive approach to regulating cryptocurrency mining due to its massive energy consumption and carbon emissions. China has implemented a crackdown on cryptocurrency mining operations, particularly those relying on coal-based electricity, in an effort to meet its national carbon reduction targets. The Chinese

government's actions have led to the closure of thousands of mining operations, with the aim of reducing the environmental burden of blockchain. In parallel, China has been promoting the development of more energy-efficient blockchain technologies, such as those utilizing renewable energy sources. While the country's crackdown on blockchain mining has been controversial, it reflects a growing recognition of the need to address the environmental consequences of the digital economy (China State Council, 2021).

Other countries have also begun to respond to the environmental concerns posed by blockchain. In Canada, for example, provinces like Quebec, with abundant hydroelectric power, have attracted blockchain miners looking for clean energy sources. However, there is growing concern about the long-term sustainability of this trend, especially as energy demand increases. In El Salvador, which adopted Bitcoin as legal tender in 2021, there have been discussions about utilizing geothermal energy from volcanic sources for cryptocurrency mining, presenting a novel approach to mitigating the environmental impact of blockchain. Despite these efforts, the global nature of blockchain means that its environmental footprint cannot be solely addressed by individual countries; international cooperation remains crucial.

To mitigate blockchain's environmental impact, various regulatory instruments can be employed. Carbon taxes and emissions trading schemes could be implemented to encourage blockchain mining operations to reduce their carbon emissions. These financial tools would create economic incentives for miners to adopt cleaner energy sources or more energy-efficient hardware. Energy efficiency standards could also be introduced, requiring mining operations to adhere to minimum energy consumption thresholds or to report their energy usage transparently. Finally, governments could implement carbon offset programs that allow blockchain companies to compensate for their emissions by investing in renewable energy projects or other carbon-reducing initiatives. These regulatory tools, while in early stages of development, offer significant potential for addressing the environmental challenges posed by blockchain technology.

In conclusion, while various countries have begun to address the environmental impact of blockchain through both national and state-level regulations, the global nature of blockchain technology calls for a coordinated international approach. A combination of regulatory tools, such as carbon taxes, energy efficiency standards, and emissions trading schemes, along with international collaboration, will be key to ensuring the long-term sustainability of blockchain in a world that is increasingly focused on environmental preservation.

5. Legal Strategies for Mitigating Blockchain's Environmental Impact

Carbon offsetting and the use of carbon credits have become key strategies in the global effort to mitigate climate change by encouraging businesses to compensate for their emissions through investments in renewable energy projects, reforestation, and other carbon-reducing initiatives. For blockchain technology, carbon offset programs present a potential solution for companies and mining operations to neutralize the environmental harm caused by their high energy consumption. One way in which blockchain-related entities could participate in carbon offsetting is by purchasing carbon credits from certified projects aimed at reducing or capturing greenhouse gases. However, the feasibility and legal challenges of implementing such programs in the blockchain sector are complex. The decentralized and borderless nature of blockchain networks makes it difficult to enforce consistent standards for carbon offsetting, and issues surrounding the transparency of carbon credits and the verification of offset projects can undermine the effectiveness of such schemes. Additionally, without a clear legal framework in place to ensure that carbon credits are accurately allocated and verified, the potential for greenwashing—where companies claim environmental benefits without substantively reducing emissions—remains a significant concern. Nevertheless, carbon offsetting could serve as a legal mechanism to reduce blockchain's environmental footprint, provided that robust verification systems and international cooperation are established to ensure the integrity of the offset projects (UNFCCC, 2021).

Energy usage regulations could play a pivotal role in encouraging blockchain systems to adopt more energy-efficient technologies and practices. Legislative approaches could require blockchain mining operations to conduct regular energy audits, providing a clear picture of their energy consumption patterns and identifying areas where efficiency improvements can be made. Moreover, governments could establish energy consumption limits for blockchain mining operations, mandating that miners reduce their energy use or transition to more efficient hardware. One example of such a regulatory tool could be the establishment of minimum energy efficiency standards for mining equipment, akin to the standards applied to other industries that rely heavily on energy-intensive machinery, such as data centers or manufacturing. Countries could also incentivize energy-

efficient practices by offering tax breaks or subsidies for blockchain companies that reduce their energy consumption or utilize renewable energy sources. The challenge in implementing energy usage regulations for blockchain lies in the difficulty of tracking energy consumption across decentralized and dispersed mining operations. This challenge could be addressed by requiring blockchain companies to report energy usage regularly or through the use of smart contracts that automatically track and verify energy consumption in real time (European Commission, 2020).

Incentivizing the shift toward greener alternatives in blockchain systems, such as the adoption of more energy-efficient consensus mechanisms, is another legal strategy that could help mitigate blockchain's environmental impact. Proof-of-stake (PoS) and other consensus mechanisms that do not require the same level of computational power as proof-of-work (PoW) have been identified as more energy-efficient alternatives. Governments could play a crucial role in incentivizing the adoption of these greener mechanisms by offering legal and financial incentives to blockchain projects that transition from PoW to PoS or other more sustainable systems. For instance, countries could introduce grants or tax incentives for blockchain startups that commit to using PoS protocols, or they could create regulations that mandate the use of less energy-intensive consensus mechanisms in certain sectors. Legal instruments such as emissions reduction credits could also be tied to the adoption of greener consensus models, further incentivizing blockchain operators to make the switch. However, the transition from PoW to PoS is not without challenges, including technological hurdles, the need for industry-wide standardization, and resistance from established blockchain projects that have already invested heavily in PoW infrastructure. Therefore, any legal efforts to promote greener consensus mechanisms will need to balance incentives with practical considerations, ensuring that blockchain innovation is not stifled in the process (Buterin, 2021).

Innovation in legal approaches could further support the environmental sustainability of blockchain technology. One potential avenue for legal innovation is the implementation of environmental reporting and transparency requirements for blockchain-based projects. Governments could require blockchain companies to disclose their environmental impact, including their energy usage, carbon emissions, and efforts to reduce their environmental footprint. Such reporting requirements could be enforced through national laws or industry-specific standards, with penalties for non-compliance. Transparency in environmental reporting would not only hold blockchain companies accountable but also allow consumers and investors to make more informed decisions about the environmental sustainability of blockchain projects. Additionally, legal innovations could include the establishment of certification programs for environmentally friendly blockchain projects, similar to certifications used in the organic food or renewable energy sectors. These certifications could provide a legal framework for identifying and promoting blockchain networks that prioritize sustainability, further incentivizing greener practices in the industry (European Commission, 2020).

6. Challenges and Controversies

The rapid pace of technological development in blockchain creates significant tension with the slower-moving nature of legal regulation. Blockchain technology evolves at a breakneck speed, with new innovations and applications being introduced regularly, often outpacing the ability of lawmakers and regulators to keep up. This speed of development makes it difficult for existing legal frameworks to adequately address the environmental implications of blockchain. Laws and regulations that might have been suitable for traditional industries are often ill-suited for the fast-moving, decentralized world of blockchain. By the time regulations are drafted and implemented, they may already be outdated or ineffective in addressing new challenges. This tension between innovation and regulation is further exacerbated by the borderless nature of blockchain, where miners and users can bypass national regulations by operating in jurisdictions with more lenient or non-existent environmental laws. As a result, regulatory bodies may struggle to create meaningful and effective policies that can keep pace with the technological advancements within the blockchain space (Mora et al., 2018).

Market resistance to stringent environmental regulations is another significant challenge in the effort to mitigate blockchain's environmental impact. Many within the blockchain community, particularly those involved in cryptocurrency mining, have historically opposed heavy regulation, citing concerns about stifling innovation and the core principles of decentralization that blockchain represents. There is a concern that over-regulation could drive blockchain innovation underground or force miners to operate in regions with looser environmental standards, where energy is cheaper and environmental regulations are less stringent. The economic incentives associated with blockchain mining, particularly in proof-

of-work systems, can create resistance to change, as miners often prioritize profitability over environmental concerns. Additionally, some blockchain advocates argue that the decentralized nature of the technology itself is inherently sustainable, as it removes the need for centralized authorities and reduces the environmental burden of traditional financial systems. However, these arguments overlook the significant energy consumption associated with blockchain mining, particularly in PoW systems, and the industry's reluctance to voluntarily adopt more energy-efficient practices. Overcoming this resistance will require a concerted effort by both regulators and industry leaders to find common ground and develop regulations that promote sustainability without stifling innovation (Cohen, 2021).

Global disparities in environmental policies further complicate efforts to regulate blockchain's environmental impact. Different countries have adopted varying approaches to climate change and environmental protection, with some implementing ambitious carbon reduction targets and others prioritizing economic growth over environmental concerns. This divergence in policies can create a "race to the bottom," where jurisdictions with weaker environmental regulations attract blockchain mining operations seeking to avoid stricter rules elsewhere. For instance, some countries with abundant, cheap electricity—often sourced from non-renewable sources—are attractive locations for energy-intensive blockchain mining operations. In contrast, countries with stricter environmental laws may face a drain on blockchain-related businesses, which could relocate to more lenient regions. This dynamic could undermine global efforts to address blockchain's environmental impact and result in fragmented regulatory approaches that fail to address the issue comprehensively. It underscores the need for international cooperation to ensure that regulatory standards are harmonized and that environmental protection efforts are not undermined by jurisdictional differences (Stoll et al., 2019).

The effectiveness of current legal frameworks in curbing blockchain's environmental impact remains a critical point of debate. While national and international legal efforts have begun to address some of the challenges posed by blockchain, it is unclear whether existing frameworks are sufficient to meet the scale of the problem. The decentralized and global nature of blockchain presents unique challenges that traditional legal systems were not designed to address. Without effective enforcement mechanisms, transparent reporting standards, and international cooperation, current legal approaches may fall short of significantly reducing blockchain's environmental footprint. As blockchain technology continues to grow and evolve, new and more innovative legal strategies will be required to mitigate its environmental impact while fostering continued technological development and innovation (Crum & Merlo, 2020).

In conclusion, the legal strategies and challenges surrounding blockchain's environmental impact are complex and multifaceted. While carbon offsetting, energy usage regulations, and incentives for greener alternatives offer promising solutions, there are significant obstacles to their implementation. Legal frameworks must evolve rapidly to keep pace with the technology, and international cooperation will be crucial in ensuring that blockchain's environmental footprint is effectively managed. Ultimately, balancing the environmental concerns with the need for innovation will be a key challenge for regulators in the coming years.

7. Future Directions and Recommendations

The potential for blockchain technology to innovate in environmentally friendly directions is significant, though the path forward will require concerted efforts from both the blockchain industry and regulators. Blockchain's decentralized and transparent nature could serve as a foundation for creating carbon-neutral or environmentally conscious systems. For example, several initiatives have already emerged that aim to reduce blockchain's energy consumption by introducing more efficient consensus mechanisms such as proof-of-stake (PoS) and hybrid models that combine PoW with PoS. The shift towards greener technologies, such as renewable energy-powered mining operations, is another promising avenue for reducing the environmental impact of blockchain networks. Moreover, blockchain's ability to track and verify environmental sustainability could facilitate more efficient carbon credit systems and help companies report their emissions more transparently. Some blockchain-based solutions are even designed to directly incentivize sustainable practices by creating decentralized platforms that reward users for adopting eco-friendly behaviors. However, these innovations remain relatively niche, and there is a need for more widespread adoption and integration into the broader blockchain ecosystem. If blockchain technology is to evolve in an environmentally friendly direction, it will require both technological advances and a shift in industry culture toward prioritizing sustainability alongside innovation (Boucher, 2020).

Stronger international cooperation is crucial for addressing blockchain's environmental impact on a global scale. While there are some international agreements focused on environmental protection, such as the Paris Agreement and the UN's sustainable development goals, these frameworks do not yet sufficiently address the specific challenges posed by blockchain technology. A coordinated global approach is necessary to set common standards and create a consistent regulatory framework that can effectively mitigate blockchain's environmental footprint. This could involve establishing international agreements or treaties focused on blockchain sustainability, which would encourage countries to adopt policies that regulate energy consumption and incentivize the adoption of environmentally friendly blockchain systems. Additionally, harmonized standards for carbon offsetting and emissions reporting in blockchain operations could be developed to ensure that all countries are held to the same environmental benchmarks. International collaboration could also promote research and development into greener blockchain technologies, enabling the global community to share best practices and solutions for reducing energy usage and carbon emissions. Given the borderless nature of blockchain, unilateral actions by individual countries are unlikely to have a lasting impact unless they are part of a larger, international strategy (Mora et al., 2018).

For national and international regulators, concrete recommendations for better integrating environmental concerns into blockchain regulation include the development of policies that require blockchain operators to disclose their environmental impact transparently. Regulations could mandate that blockchain projects, particularly large-scale operations like cryptocurrency mining, provide detailed reports on their energy consumption and carbon emissions. Such transparency would help consumers, investors, and regulators understand the environmental costs of blockchain and could drive a shift toward more sustainable practices. Additionally, governments could introduce tax incentives or subsidies for blockchain companies that adopt energy-efficient technologies or renewable energy sources. These financial tools would make it economically viable for smaller blockchain operations to transition to greener practices. At the international level, regulators should work towards creating a global certification system for environmentally sustainable blockchain networks, which could be recognized across borders. Policymakers should also prioritize the creation of emissions trading schemes and carbon pricing mechanisms that hold blockchain companies accountable for their carbon footprint, similar to the systems already in place for industries like aviation and manufacturing. By integrating these legal tools into the regulatory framework, both national and international regulators could ensure that blockchain's environmental impact is significantly reduced without stifling innovation (European Commission, 2020).

Opportunities for collaboration between blockchain developers and environmental organizations could further help reduce blockchain's environmental footprint. Blockchain technology can be leveraged to enhance transparency and accountability in environmental initiatives, creating decentralized platforms that track carbon emissions, energy consumption, and sustainability efforts across various industries. By collaborating with environmental organizations, blockchain developers can ensure that their technologies align with global sustainability goals and adopt best practices for energy efficiency. One potential area for collaboration is the development of blockchain-based carbon credit systems that allow individuals and companies to offset their carbon emissions through verified, transparent transactions. Blockchain's ability to securely track and verify such transactions makes it an ideal technology for ensuring the integrity of carbon credit markets. Additionally, environmental NGOs and blockchain developers can work together to design blockchain solutions that incentivize users to adopt more sustainable practices, such as reducing energy consumption or investing in renewable energy projects. This collaboration could take the form of public-private partnerships, where both sides bring their expertise to the table to design innovative solutions that address both environmental and technological challenges. By working together, the blockchain industry and environmental organizations could create a more sustainable future for the technology (Buterin, 2021).

8. Conclusion

This review has examined the environmental impact of blockchain technology, highlighting the significant challenges posed by its energy-intensive consensus mechanisms, particularly in proof-of-work systems. The carbon emissions associated with blockchain mining, as well as other environmental concerns such as e-waste, present a pressing need for legal intervention. While there is potential for blockchain to evolve in an environmentally sustainable direction through technological innovation, such as the adoption of greener consensus mechanisms and renewable energy-powered operations, the current regulatory landscape remains insufficient to address the full scale of the problem. International legal frameworks need to be strengthened

to create consistent standards for energy consumption and carbon emissions, while national regulators should implement policies that incentivize energy-efficient practices and require greater transparency from blockchain operators. Collaborative efforts between blockchain developers and environmental organizations could also play a vital role in reducing blockchain's environmental footprint, enabling the industry to align with global sustainability goals.

As blockchain technology continues to grow and evolve, it is imperative that legal frameworks keep pace with these developments to ensure that innovation does not come at the expense of the planet. A more coordinated, forward-thinking approach to regulation is needed—one that balances technological progress with environmental sustainability. Policymakers, industry leaders, and environmental organizations must work together to create legal strategies that promote greener blockchain systems, drive innovation in sustainability, and mitigate the negative environmental impacts of this transformative technology. Only through such collective action can blockchain realize its potential while contributing to the global fight against climate change (Stoll et al., 2019).

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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