Received: 16 November 2024 | Revised: 17 February 2025 | Accepted: 27 February 2025 | Published online: 18 April 2025

REVIEW

FinTech and Sustainable Innovation
2025, Vol. 00(00) 1–13
DOI: 10.47852/bonviewFSI52024817

BON VIEW PUBLISHING

The Evolution of Sustainable Investment: The Role of Decentralized Finance and Green Bonds in the Efficiency and Transparency of Green Finance

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Abstract: Green finance is a cornerstone of sustainable investment, but it highlights the critical importance of transparency, traceability, and financial efficiency within an environmental, social, and governance framework. This review article examines the potential of green finance as a pillar for accelerating investment in sustainable pathways, particularly using green bonds and the innovative mechanisms offered by decentralized finance (DeFi). Green bonds are highlighted as a key instrument for channeling capital toward green projects, while DeFi is explored as an innovative tool with the potential to democratize access to finance and enable micro-investments in sustainability projects with a relevant social impact. This article examines both mechanisms in terms of their ability to increase the efficiency and reliability of green finance ecosystems. The analysis also explores emerging challenges such as regulatory constraints, the threat of greenwashing, and technological limitations associated with the implementation of blockchain and artificial intelligence. By addressing these barriers, the article provides strategic recommendations for achieving greater transparency and reliability in green finance markets, thereby fostering investor confidence and broader market growth. It also identifies research gaps and proposes new avenues to advance the integration of sustainable finance, ensuring its scalability and inclusion in the promotion of global sustainability.

Keywords: green finance and sustainable investment, decentralised finance (DeFi), financial transparency and efficiency, blockchain

1. . Introduction

Green finance has emerged as an essential mechanism for aligning financial markets with sustainable development goals [1, 2], promoting practices that not only minimize harm but also actively contribute to global sustainability [3, 4]. Green finance encompasses a range of activities and financial instruments designed to support projects that generate a positive environmental and social impact, integrating environmental, social, and governance (ESG) factors into financial decision-making processes [5–7].

The principal objective of environmental finance is to provide financial instruments that facilitate sustainable development, prioritizing transparency, traceability, and financial efficiency [8, 9]. The accelerated expansion of green finance not only signifies a transition in financial systems to reduce environmental harm but also strives to proactively advance global sustainability [10]. The key components of this shift include the transparency of ESG reporting, the reliability of green bonds as sustainable investment vehicles, and the transformative potential of decentralized finance (DeFi) to enable inclusive and accessible impact investments [11].

This review article examines the principal approaches and theories that underpin the significance of green finance in sustainability, addressing three key areas: (1) transparency and traceability in ESG reporting, (2) the efficiency of green bonds as sustainable investment vehicles and (3) the transformative role of DeFi in enabling micro-investments in impact projects. A critical and comparative analysis is conducted to identify gaps and potential avenues for advancement in the field of green finance.

2. The Efficiency and Transparency of Green Bonds

Green bonds have become a fundamental component of the financial infrastructure supporting the transition to sustainable development. They offer structured mechanisms for financing environmentally friendly initiatives, as evidenced by the literature [12]. Green bonds have emerged as a crucial instrument for financing sustainable initiatives, offering a structured way of channeling capital into projects that promote the transition to an economy with a lower environmental impact, thereby reducing environmental degradation, mitigating climate change, and promoting social development [13–15]. However, for this type of funding to be reliable, it is imperative to guarantee transparency in its use and the traceability of environmental results [16]. Indeed, transparency guarantees investor confidence, while efficiency ensures that resources are optimized for environmental impact [17, 18].

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2.1. The use of blockchain and artificial intelligence to enhance transparency in green bonds

Blockchain technology and artificial intelligence (AI) have been put forth as potential tools to enhance the process of verifying and monitoring green bonds [19, 20]. These technologies facilitate the creation of immutable records and the automation of compliance processes through smart contracts, thereby ensuring that funds are used exclusively for their intended environmental purposes [21, 22]. In a comparative analysis, Karakostas and Pantelidis [23] demonstrate that these technologies can also mitigate the risk of misappropriation of funds and enhance investor confidence. The integration of blockchain and smart contracts enables DeFi applications to facilitate access to impact investments for small investors, thereby democratizing financial systems that have traditionally been dominated by large operators and enhancing their inclusivity [24–26].

AI can enhance the functionality of blockchain technology by automating compliance and sustainability reporting processes [27, 28]. By employing machine learning algorithms, AI systems can analyze extensive data sets to detect and identify anomalies, predict risks, and ensure that projects adhere to pre-established ESG criteria [29–31]. Subsequently, the integration of smart contracts into blockchain-based platforms can facilitate further operational simplicity through enabling the automatic release of funds when specific sustainability milestones are met [32].

2.2. Challenges and recommendations for green bond transparency

Despite their potential, these technologies encounter obstacles, including disparate regulatory frameworks, considerable implementation costs, and the risk of greenwashing [33–35]. It is of the utmost importance to ensure the efficiency and transparency of green bonds to increase investor confidence and facilitate market growth [36]. Jeevitha and Bhanumathi [37] posit that greater standardization of the criteria for green bond certification at an international level would contribute to investor confidence.

The absence of a uniform regulatory framework gives rise to regulatory fragmentation, which in turn serves to heighten the risk of greenwashing [38]. This is because companies are at liberty to comply selectively with the sustainability standards that are least stringent in certain jurisdictions [39]. The result of this regulatory inconsistency is a reduction in investor confidence and a concomitant difficulty in assessing the genuine environmental impact of green bond projects [40]. This, in turn, has a deleterious effect on the credibility of the green finance market.

The development of interoperable blockchain systems has the potential to facilitate cross-border investments by enabling real-time data sharing between issuers, investors, and regulators [41, 42]. It is imperative that collaborative efforts are undertaken between industry stakeholders, regulators, and technology providers to create a cohesive ecosystem that strikes a balance between innovation and accountability [43–45]. To achieve this objective, capacity-building initiatives should concentrate on providing stakeholders with the requisite knowledge and tools to enable the effective adoption of emerging technologies [46–48]. Furthermore, the costs of implementation, the energy consumption of blockchain networks, and the necessity for regulatory clarity also present considerable obstacles [49–51]. It is imperative that future advances prioritize the development of low-energy blockchain solutions and establish standardized protocols for AI in green finance to maximize the potential of these technologies.

The growth of green bonds and sustainability financing based on DeFi is substantially hindered by regulatory discrepancies between nations [52]. While the European Union (EU) has instituted a stringent regulatory framework through mechanisms such as the EU Green Bond Standard, the Sustainable Finance Disclosure Regulation (SFDR), and the Corporate Sustainability Reporting Directive (CSRD), other regions, such as the United States, function with more fragmented policies, and sustainability disclosure is voluntary [53–56]. This absence of uniformity engenders considerable uncertainty for investors, imposes compliance burdens, and heightens the risk of greenwashing [57]. In contrast, China has implemented substantial state incentives to expedite green financing, yet it grapples with concerns pertaining to transparency and cross-border harmonization [58]. Financial regulators have articulated green financing policies, but there are inconsistencies in ESG assessment criteria and data accessibility for foreign investors seeking standardized sustainability metrics [59].

In the context of DeFi mechanisms, the issue of regulatory uncertainty is of particular significance [60]. The absence of a clearly defined global regulatory framework pertaining to smart contract compliance, decentralized governance models, and financial risk mitigation has resulted in investor hesitation [61]. In the absence of a harmonized legal framework, the potential of DeFi to democratize green investments remains constrained, as investors encounter challenges related to legal liability and the security of funds [62].

In conclusion, it is essential that regulators and industry leaders collaborate to establish global guidelines and standards, thereby reducing regional variations and promoting transparency in the industry. Furthermore, technological advances, in particular blockchain and AI, have demonstrated significant potential to strengthen the credibility and traceability of green bonds.

3. Decentralized Finance and Micro-Investments in Sustainability

DeFi has emerged as an innovative model for the democratization of access to sustainable finance. DeFi represents a radical innovation in the field of green finance, introducing a disruptive approach by eliminating traditional intermediaries such as banks and other financial institutions [63–65]. The model is made possible by the utilization of technologies based on blockchain and smart contracts, which facilitate enhanced transparency and accessibility [66].

The removal of intermediaries through DeFi results in a reduction in transaction costs and an expansion of the reach of sustainable finance. This enables small investors, who have previously been excluded from the conventional financial market, to participate in investments with a positive environmental impact, thereby promoting a more inclusive financial ecosystem [67, 68]. These characteristics render DeFi a potent instrument for democratizing access to the capital requisite for financing sustainability projects [69, 70].

Blockchain and smart contracts constitute the technological foundation of DeFi, offering unparalleled transparency and efficiency [71, 72]. These technologies facilitate the automated execution of investment terms based on predefined ESG criteria, reducing the administrative burden and ensuring accountability [73–75].

3.1. Inclusive access and democratization of sustainable investments

DeFi represents a transformative change in green finance by breaking down traditional barriers to entry and enabling wider participation in sustainable investments [76]. One of the principal

characteristics of DeFi is its capacity to democratize financial access, thereby enabling small investors and traditionally marginalized communities to contribute to and benefit from sustainability projects [77, 78]. Through innovative mechanisms such as blockchain and smart contracts, DeFi platforms facilitate the pooling of resources from diverse investors to finance large-scale projects, thereby strengthening inclusion and equity in green finance [54, 79,80].

An expanding corpus of evidence indicates that DeFi has the potential to facilitate the formation of decentralized autonomous organizations (DAOs), which pool capital from small investors to finance large-scale sustainability projects. This is evidenced by the following sources: [81–83]. Schellinger et al. [84] highlight that these decentralized structures reduce transaction costs and increase accessibility, thus enabling investors with limited capital to participate in impact investments. Conversely, DeFi applications frequently employ smart contracts, which enable the automated fulfillment of investment conditions based on predefined ESG criteria, thus increasing efficiency and facilitating more straightforward, transparent, and accessible impact investments [85–87]. It is this efficiency that renders it feasible for minor investors to participate in impact investments that were heretofore accessible solely to institutional actors, while smart contracts guarantee that investments align with predefined ESG criteria, thereby mitigating the risks of default or misallocation of funds [88, 89].

The interrelationships between the concepts can be represented in a concept map, which provides a summary of the principal elements of green finance, DeFi, and ESG practices. Figure 1 illustrates the way blockchain and the principles of transparency and efficiency contribute to the democratization of investments while also demonstrating the challenges that must be overcome, including greenwashing and the necessity for global standardization.

3.2. Challenges and proposals for strengthening DeFi in green finance

Despite its potential, DeFi is confronted with significant challenges, including the absence of global regulatory oversight and the inherent risks associated with the complexities of security and technology [26, 90]. Alamsyah et al. [91] put forth the proposition of establishing international regulatory standards for DeFi, which they posit would serve to mitigate uncertainty and enhance security.

It is evident that a plurality of approaches exists regarding this issue. For instance, the EU has assumed a leading role in the regulation of sustainable finance through the European taxonomy, the SFDR, and the CSRD [92–96]. The instruments seek to standardize the definitions of sustainable investments and increase the transparency of financial markets [97], although the high level of bureaucracy and difficulties in implementing them in different countries are major challenges [98].

In contrast, the United States has a less centralized regulatory framework and is dependent on bodies such as the Securities and Exchange Commission and the Federal Reserve [66, 99]. The most recent significant regulation is the Climate Disclosure Rule, which requires companies to report climate risks [100]. This approach is highly flexible and adaptable to market dynamics and continuous financial innovation [101]. However, it faces limitations in terms of standardization, political resistance, and dependence on voluntary initiatives [102].

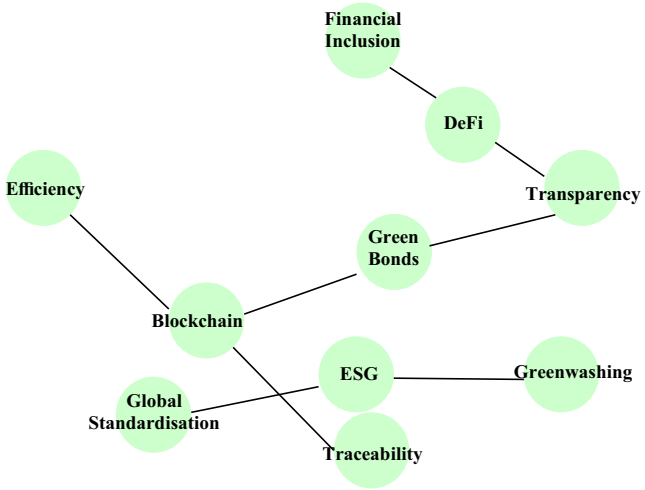
Finally, a third example is China, which has developed a robust green bond market that is regulated by the People's Bank of China and the Securities Regulatory Commission [103–105]. Concurrently, China has implemented the Green Finance Guidelines but faces challenges in terms of transparency and harmonization of standards [106–108]. This strategy is based on strong incentives for the accelerated growth of the sustainable sector [109]. Nevertheless, challenges pertaining to transparency and the implementation of coherent regulations must be given due consideration [92, 110].

The technological complexity of DeFi platforms, coupled with the limited technological literacy of potential users and the prevailing regulatory uncertainties, continue to impede the widespread adoption of these platforms [111, 112]. The resolution of these obstacles necessitates a unified effort to advance financial literacy, develop user-friendly interfaces, and establish global regulatory standards [100, 113,114]. Chohan [115] proposes the creation of measures to safeguard against fraud and technological vulnerabilities.

The most pressing of these consequences is the obstruction of international investment flows in the field of green finance, as regulatory disparities create a high bureaucratic burden and a lack of clarity for global investors and financial institutions [116]. This obstruction is created by divergent green bond certification requirements, differences in ESG reporting metrics, and varying DeFi governance structures [117]. This fragmentation reduces market efficiency, increases legal risks, and discourages the allocation of multinational capital to sustainable projects [118].

It is imperative that future research examines the potential of regulatory models that can guarantee security and flexibility for DeFi, thus supporting its continued evolution as a tool for green finance.

Figure 1
Interconnections between green bonds, DeFi, and ESG



4. Transparency in ESG Reporting and Reducing Greenwashing

The reliability of ESG reporting is of paramount importance in ensuring the effectiveness and transparency of sustainable investments, as well as in promoting accountability and trust among investors [119–121]. As Li et al. [122] observed, blockchain technology has the potential to facilitate the real-time monitoring of ESG compliance, thereby reducing greenwashing practices and enhancing investor confidence. Greenwashing, defined as the misrepresentation of sustainability practices or the misleading claim of a company's positive environmental impact, undermines

stakeholder trust and damages the credibility of green finance initiatives [123–125].

Zhao [126] posits that blockchain-based systems provide a dependable infrastructure for monitoring ESG metrics, thereby facilitating the attraction of investors who are inclined to favor sustainable and ethical practices. Furthermore, the integration of AI can extend the advantages of blockchain technology by enabling the automation of ESG performance analysis and the identification of inconsistencies or fraud in reported data, thereby enhancing transparency and accountability [127–129].

Nevertheless, despite these technological advancements, there are numerous limitations that jeopardize the effectiveness of these systems. First, the absence of globally standardized ESG metrics presents a significant challenge in terms of data comparison and integration [130–132]. Furthermore, the fragmentation of data sources results in significant gaps, thereby reducing the reliability of analyzes [133, 134]. The implementation of blockchain technology, although promising, is confronted with several practical challenges, including high initial costs, technological barriers in emerging markets, and concerns about the scalability of solutions [135–137].

The absence of harmonized global regulations and the reluctance of stakeholders from disparate sectors and regions to collaborate further impedes the adoption of ESG systems on a global scale [138, 139]. This underscores the imperative for integrated policies, government incentives, and public-private partnerships to develop more robust and accessible ESG systems that can sustain responsible and reliable investment practices on a global scale.

4.1. Utilization of blockchain for ESG and standardization recommendations

To ensure the consistency of ESG reporting, it is recommended that regulations be harmonized on a global scale, thereby facilitating the implementation of a unified certification system [139–142]. This global initiative has the potential to reduce the phenomenon of greenwashing and facilitate access to reliable ESG data [143–145]. As evidenced by studies such as Baldi and Pandimiglio [146], standardizing ESG reporting in the financial sector is crucial to guarantee data integrity.

Conversely, disparate approaches to ESG regulation are observed across different countries, which presents a challenge in the development of unified blockchain solutions [147]. Bischoff and Seuring [148] emphasize the necessity to streamline the storage of ESG tracking data, which currently presents several practical limitations that must be addressed for the widespread adoption of blockchain technology. Moreover, the incorporation of AI into blockchain systems can facilitate the analysis of ESG data, enhancing the ability to identify patterns and anomalies [149]. This integration is particularly beneficial for large-scale projects involving multiple stakeholders, where the complexity of data management often leads to inefficiencies [150].

To address the high energy consumption of blockchain technologies, future developments should focus on energy-efficient solutions, such as proof-of-stake consensus mechanisms and the use of renewable energy sources.

4.2. The challenges of ESG reporting and greenwashing

Despite the potential benefits, ESG reporting is confronted with considerable obstacles, including inconsistencies in data and the absence of universally accepted metrics [151–153]. These issues serve to complicate the implementation of blockchain-based solutions and impede the global scalability of ESG initiatives [88]. Furthermore, the phenomenon of greenwashing persists, with some corporations exploiting the lack of transparency to misrepresent their sustainability practices [154, 155].

To overcome these challenges, it is imperative that policymakers and industry leaders collaborate to develop comprehensive frameworks that address the complexities of ESG reporting. Key concerns should focus on global harmonization of ESG standards, strengthening regulatory oversight, capacity building and training on the relevance of accurate ESG reporting, and encouraging the adoption of advanced technologies supported by blockchain and AI technologies to improve ESG reporting.

5. Methods

This review article aims to systematically evaluate the evolution of sustainable investment, analyzing the role of blockchain and AI in green finance. The article applies a structured methodology that aims to enable and enhance its replicability and robustness [156, 157]. Data was collected based on a selection of analyzed case studies, with a focus on platforms such as ClimateTrade and WePower that use blockchain for green finance [158–162]. Conversely, evaluation metrics were utilized to assess the effectiveness of blockchain and AI. This was based on the use of predefined key performance indicators, such as transparency, traceability, energy efficiency, and scalability, ensuring an evidence-based comparison [163–169].

Finally, a comparative analysis was carried out. Green bond applications employing blockchain were compared with traditional financing methods, assessing improvements in terms of efficiency and reliability [68, 69,75, 170]. AI-based platforms were analyzed to determine their capacity for anomaly detection and predictive risk management in ESG compliance [171, 172]. This structured approach aims to highlight actionable insights and identify replicable strategies for potential stakeholders, addressing the challenges in implementing these technologies in green finance ecosystems [173].

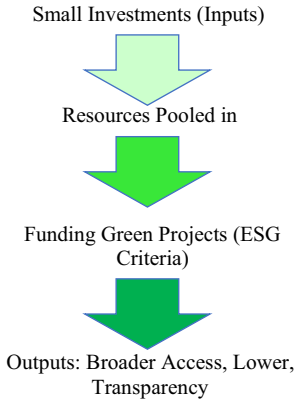
6. Results

This review article draws several conclusions that are of particular significance. First, it highlights significant improvements in the efficiency and transparency of green finance when blockchain and AI are applied [174, 175]. The analysis emphasises several key conclusions, including significant efficiency gains achieved in green bonds [176, 177]. Indeed, case studies of platforms such as ClimateTrade have demonstrated that blockchain-based green bonds have been shown to engender cost savings of between 15 and 25% in transaction costs when compared to traditional methods [178]. Additionally, the review emphasizes enhanced traceability of funds, with stakeholders able to access real-time updates [178] (see Table 1).

Table 1
Comparison of green bonds

Metric	Traditional Green Bonds	Blockchain-Based Green Bonds
Transaction costs	High (5–10%)	Low (1–3%)
Transparency	Moderate	High
Traceability	Limited	Real-time
Processing time	2–4 weeks	1–3 Days

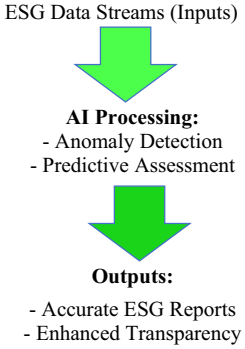
Figure 2
DeFi's role in green finance



On the other hand, DeFi platforms have the potential to increase scale. These platforms enable micro-investments in green projects and provide greater access to finance for groups that previously had difficulties, reducing transaction costs and enabling micro-investments [69, 179,180] (Figure 2).

AI tools have the potential to simplify ESG compliance processes by reducing reporting errors and enhancing the detection of anomalies, including greenwashing practices [178–181]. Platforms such as Sensefolio have provided predictive insights into ESG compliance risks, improving decision-making for investors [182] (Figure 3).

Figure 3
AI automation in ESG reporting



All these results demonstrate the increasingly important role that these new ways of financing have acquired, both because of their ease and democratization and because of their greater transparency.

7. Discussion and Limitations

The conclusions of this review article are consistent with extant theories concerning the transformative potential of blockchain and AI in the field of green finance while concomitantly addressing the principal challenges that stand in the way of widespread adoption. Indeed, empirical data demonstrates that DeFi platforms increase access to sustainable finance for underserved groups; for instance, projects supported by DAOs reported an increase in the participation of small investors, thus highlighting DeFi's ability to democratize access to green investments.

Despite the potential of AI and blockchain to enhance ESG reporting, limitations in global standardization and regulatory inconsistencies persist as significant barriers. Case studies demonstrate that platforms utilizing these technologies have successfully reduced compliance errors. However, the absence of universal ESG metrics hinders cross-border implementations. While blockchain ensures transparency and traceability, its environmental cost, characterized by significant energy consumption, necessitates consideration. Emerging solutions, such as proof-of-stake protocols, offer a potential mitigation strategy for these environmental impacts.

It is anticipated that the green finance sector will be subject to transformative regulatory changes in the future, driven by the necessity for greater standardization and transparency. Primarily, a transition toward global ESG harmonization will be pivotal, with organizations such as the International Sustainability Standards Board and the Financial Stability Board playing a pivotal role in establishing unified sustainability disclosure standards.

Concurrently, governments and financial regulators are exploring the potential of blockchain-based compliance tools to facilitate real-time monitoring of green bond transactions and ESG impact tracking. Finally, advancements in AI are poised to automate ESG assessments, ensuring that companies and financial products meet standardized sustainability criteria. In response to these evolving trends, policymakers must adapt regulatory frameworks to strike a balance between flexibility and security, thereby fostering innovation while safeguarding investor protection and financial stability.

Nevertheless, a significant challenge to the establishment of globally consistent sustainability regulations is the increasing geopolitical tension between the major economies. The EU and China have adopted ambitious green finance policies, yet their respective priorities diverge. The EU emphasizes the implementation of stringent ESG disclosure regulations, whereas China places emphasis on state incentives for green investment. Conversely, the regulatory approach of the United States is characterized by its distribution and fragmentation, with a primary focus on market-oriented principles. The heterogeneity of these regulatory frameworks poses significant challenges to the harmonization of processes and the enhancement of international cooperation, impeding the optimization of green finance on a global scale.

8. Conclusions and Areas for Future Research

The integration of green finance with emerging technologies, including DeFi and blockchain, represents a paradigm shift in the way sustainability can be incorporated into global financial systems. This shift illustrates the essential requirement to enhance transparency, efficiency, and inclusivity in sustainable investment practices. Nevertheless, its complete potential remains constrained and unrealized due to the persistence of significant challenges, including regulatory inconsistencies, security vulnerabilities, and the environmental costs associated with technological implementation.

To address these challenges, a future research agenda should be developed that prioritizes the creation of globally harmonized regulatory frameworks, with the objective of enabling them to balance flexibility and security. It is essential that such frameworks take into account the specific requirements of different jurisdictions while simultaneously promoting cross-border collaboration with the objective of simplifying green financing practices. Furthermore, research into alternative blockchain technologies that minimize

environmental impact could markedly enhance the scalability of sustainable finance solutions.

Further investigation is required to evaluate the social and economic consequences of DeFi on green finance. It is of particular interest to consider the potential for reducing wealth inequalities, increasing access to financial services for underserved communities, and democratizing investments in sustainability projects. Another promising avenue of research involves the development of advanced metrics and methodologies to quantify ESG impacts, allowing for more accurate evaluation and communication.

9. Recommendations and Practical Solutions for Advancing Green Finance

For green finance to advance and become a cornerstone of the global economy, it is essential that a multifaceted approach is adopted, which encompasses policy reform, the integration of technological innovation, and the development of collaborative initiatives. First, it is of the utmost importance to establish a global regulatory standard for green bonds and DeFi ecosystems. The establishment of harmonized international frameworks will serve to reduce uncertainty and fear while simultaneously creating a level playing field for investments in sustainable finance. It is incumbent upon financial institutions to collaborate closely with governments and other regulatory to develop and implement comprehensive regulations on ESG certification. This will ensure that the criteria remain robust, transparent, and resistant to greenwashing practices.

Second, it is essential to enhance the technological infrastructure that underpins green finance. Blockchain and AI have the potential to transform ESG traceability, compliance verification, and fraud risk mitigation. Investment in low-energy blockchain solutions and AI-based ESG analyses is imperative for the reduction of the environmental impact of these technologies while increasing efficiency and reliability. The implementation of innovative financial technologies, such as automated reporting systems and real-time monitoring of environmental impacts, could also serve to reinforce investor confidence.

Furthermore, the establishment of information initiatives targeting investors, businesses, and policymakers is essential for enhancing awareness of the opportunities and risks associated with green finance. By fostering a culture of informed decision-making, the sector can overcome obstacles such as investors' limited knowledge and resistance to adopting new technologies.

Acknowledgment

The author would like to thank CEFAGE and CIGEST for supporting her research.

Funding Support

The review article was not financially sponsored.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

Conflicts of Interest

The author declares that she has no conflicts of interest regarding this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data was created or analyzed in this study.

Author Contribution Statement

Natália Teixeira: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition.

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How to Cite: Teixeira, N. (2025). The Evolution of Sustainable Investment: The Role of Decentralized Finance and Green Bonds in the Efficiency and Transparency of Green Finance. *FinTech and Sustainable Innovation*. https://doi.org/10.47852/bonviewFSI52024817