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Research article

Digital green finance models for sustainable urban development: Current trends and future perspectives

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Abstract: The widening global deficit in sustainable urban infrastructure financing highlights the limitations of conventional financial models. Although green finance instruments and digital financial technologies have expanded rapidly, their roles within financing structures for sustainable urban development remain fragmented and insufficiently synthesized. This study systematically identifies key green finance structures and digital technologies that enhance their operation in facilitating sustainable urban development. The study adopts a mixed-method systematic review conducted in two phases. A total of 113 articles were drawn from the literature for bibliometric analysis, and 33 articles were selected for further systematic analysis. The results of the bibliometric analysis indicate that sustainable urban transitions are propelled by synergistic relationships among governmental policies, green finance structures, and digital technologies. Three dominant themes—organized around government-led initiatives for urban sustainability, financing structures for low-carbon cities, and digital innovations for green finance—were identified. The results from the systematic analysis identified revolving funds and green public–private partnerships as key financing structures. Also, integration of blockchain and tokenization, artificial intelligence and big data analytics, and digital finance platforms into the financing structures are the most viable means of facilitating and expanding green finance for sustainable urban

development. The findings of the study provide policymakers and stakeholders with a comprehensive understanding of the complexities of integrating digital innovations into a green financing structure. Furthermore, the study provides a pragmatic foundation for structuring policy and corporate strategies that integrate digital innovation into green finance structures.

Keywords: digital innovation; green finance; sustainable urban development; blockchain; big data; artificial intelligence; digital finance

JEL Codes: G10, G20, Q01, R30, R51

1. Introduction

Recent years have witnessed an accelerating global urbanization, which has fundamentally transformed sustainable financing dynamics (Lin et al., 2025; Shen et al., 2024). Urban development consumes most global energy resources while generating approximately 75% of worldwide carbon emissions and accommodating over 4 billion people (Supriatna and Lenz, 2025). It has been predicted that this urban population will reach nearly 70% by 2050, creating unprecedented demand for sustainable urban infrastructure (Khaleel et al., 2024). Thus, it is imperative that investments are made into developing sustainable urban infrastructure that meets current and future demands.

Green finance has emerged as an instrumental financing model to address the shortfalls in investments for sustainable urban development. Green finance is defined as the process of pooling and distributing financial resources to initiatives that promote sustainable development (Wang et al., 2022). It is a prominent mechanism by which environmental and sustainable solutions are incorporated into financial decision-making and allocation to address prevailing sustainable development challenges. Green finance has gained traction in recent times. From 2012 to 2022, the green finance market experienced a dramatic surge in its share of the global finance market. Its market share rose from a meagre 0.1% to 4% of global assets, with its issuance volumes increasing from approximately US$5 billion to an astronomical US$600 billion over the same period (Pertseva and Vityazeva, 2024). This is consistent with the volume of traction sustainable development has gained over the same period. It is also a reflection of the attention being given to sustainable solutions to safeguard the planet.

Multiple financial tools have been used to facilitate green finance. These include green bonds, sustainability-linked debt, green loans and credit, and green mortgages. Green bonds are debt instruments used to raise capital for initiatives with environmental benefits. The purpose of green bonds is to court the interest of investors to commit to projects that promote sustainable development (Shi et al., 2023). Sustainability-linked debt is a relatively new green financing tool. Its first recorded issuance was in 2019 when the utility firm Enel S.p.A issued a €2.5 billion sustainability-linked bond. Sustainability-linked debt is a financing tool used to raise capital for projects that incorporate sustainability performance targets (SPT) (Mariani et al., 2025). It is distinct from green bonds in that green bonds are intended to raise capital to finance "green" projects. Investors in green bonds hold green assets. However, with sustainability-linked debt, the capital raised may be for general corporate or business purposes with predefined targets for sustainability performance. It encourages corporate stakeholders to incorporate "green" into their regular business models.

Green loans have also gained traction over the past decade as a key financing instrument for promoting green solutions. Studies show that green loans demonstrate lower default risk compared to conventional loans, making them attractive to financial institutions while channeling capital toward environmental projects (Neagu et al., 2024). They are debt instruments that are made available to borrowers for the exclusive purpose of financing green projects (Gilchrist et al., 2021). Green credit lines are usually provided by Development Finance Institutions (DFIs) and disbursed through the local banks to borrowers with the purpose of funding green projects. Green credit lines have extended repayment periods, lower interest rates, and technical assistance to aid in the successful delivery of green projects (Brears, 2022). Though similar, green loans and green credits have distinct modes of operation. While green loans are provided as a single lump-sum disbursement for a defined green project with a defined repayment period, green credits are provided as a flexible, continuous financial facility meant to support a borrower's portfolio of green projects. Funds can be re-borrowed upon repayment in a process similar to the conventional line of credit. Gilchrist et al. (2021) highlighted this revolving nature as a key distinction from traditional green loans. Brears (2022) also noted that this flexibility allows DFIs to support multiple projects with a single capital pool. Neagu et al. (2024) provided evidence that this structure reduces risk for lenders while maintaining project-level accountability.

A green mortgage is a green financing tool used to incentivize households and individuals to purchase energy-efficient properties or retrofit existing facilities (Devine and McCollum, 2022). They are also known as energy-efficient mortgages (EEM). The incentives provided by green mortgages include lower interest rates, longer repayment periods, and cash rebates. Green mortgages are offered by lending institutions to promote sustainability, providing preferential terms to households and individuals with high energy performance certificates or additional funding for energy retrofitting of existing buildings (Migliorelli and Dessertine, 2019).

The aforementioned financing tools are specifically tailored to facilitate green financing toward sustainable urban development. However, it is imperative to situate financial tools within financial structures that facilitate their efficient delivery. In recent times, digital technologies and innovations have significantly influenced the operation of financial structures in utilizing financial tools to raise and administer funds for sustainable urban development. Digital technologies and innovations wield enormous potential to widen the net of potential investors, increase capital, and enhance transparency and security. Considering the fact that the annual financial shortfall for sustainable development is estimated to be $4 trillion and urban infrastructure alone demands approximately $2.7 trillion annually across low/middle-income countries, it is imperative to evaluate novel ways by which digital technologies and innovations enhance the operation of financial structures to maximize gains from financial tools to facilitate green financing (Giroud, 2024). While existing studies have examined green finance tools or digital technologies in finance separately, there remains a gap in understanding how digital technologies can be strategically integrated into financial structures to optimize the deployment of green finance tools for sustainable urban development. Previous reviews have catalogued either finance mechanisms or digital innovations in isolation, but few have systematically explored their intersection and practical integration pathways (Palmaccio et al., 2023; Bibri et al., 2023; Broby and Yang, 2025). Currently, there are limited studies that identify, explore, and consolidate the current and potential use of digital technologies and innovations in enhancing financial structures to optimize the use of financial tools and facilitate green finance for sustainable urban development.

To address this gap, this study conducted a mixed-method systematic review of relevant literature to identify the most relevant finance structures facilitating green finance and explore the digital

technologies that enhance their operation. Unlike previous reviews, this study uniquely examines three integrated dimensions: the digital technologies, the financial structures they enhance, and the green finance tools these structures deploy. The study evaluated the significance of the identified technologies to finance structure operations and explored practical integration methods. This integrated approach moves beyond cataloguing innovations to provide actionable insights on maximizing capital mobilization for the $4 trillion annual financing shortfall. For policy and corporate decision-making, the findings serve as a viable guide for integrating digital innovation into green finance structures.

2. Methodology

This systematic literature review (SLR) adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol. This approach facilitated the identification, analysis, and reporting of relevant findings on digitally enhanced green financing models for sustainable urban development. The methodology guarantees that research is executed and documented with rigor and efficacy, as evidenced in sustainable finance studies (Lin et al., 2025; Shen et al., 2024). The process was executed in three phases, as detailed in the subsequent section.

2.1. Search strategy

The research process commenced with a search for relevant publications within the domain, as data collection from previous studies is essential for identifying knowledge gaps and formulating significant conclusions. A preliminary search was therefore conducted, resulting in the identification of suitable keywords and a database to guarantee successful results. The Scopus database was utilized to retrieve relevant articles, as it is recognized as credible and comprehensive for systematic reviews, providing extensive coverage for interdisciplinary research. The search query employed in the Scopus database for article selection was as follows: TITLE-ABS-KEY((“green finance” OR “green bond*” OR “green bank*” OR “sustainable finance” OR “sustainability-linked loan*” OR “climate finance” OR “ESG invest*” OR “impact invest*” OR “blended finance”) AND (“sustainable urban development” OR “sustainable city” OR “smart city” OR “low carbon city” OR “climate neutral city” OR “urban sustainability” OR “urban transition” OR “urban resilience” OR “SDG 11”)).

2.2. Study selection process

The initial search produced 113 publications from the Scopus database as of September 3, 2025. These were filtered using predefined inclusion and exclusion criteria to ensure quality and relevance. The inclusion criteria comprised peer-reviewed journal articles and conference papers published between 2013 and 2025 in English. Articles had to explicitly address at least two of the following domains: green finance structures, digital technologies, or sustainable urban development. The exclusion criteria eliminated editorial notes, book chapters, and non-peer-reviewed publications. Studies focusing solely on traditional finance without sustainability components were excluded, as were articles discussing digital technologies without finance applications. Publications lacking sufficient methodological information or adequate data on green financing mechanisms were also removed. Formal quality appraisal tools were not employed in article selection. The selection process relied on predefined criteria, with manual screening based on the relevance to the research objectives.

This approach was adopted due to the exploratory nature of this emerging field and its focus on mapping integration pathways. This limitation is acknowledged, and future reviews would benefit from incorporating standardized quality assessment tools such as MMAT or JBI critical appraisal checklists. This process yielded 81 publications for subsequent screening and analysis. The titles and abstracts of these publications were evaluated to exclude articles that did not correspond with the study's scope and objectives. This screening removed 32 articles, including 18 articles addressing contexts beyond urban development and 14 abstracts lacking adequate information regarding green financing mechanisms or digital innovation integration.

Following title and abstract screening, full-text screening was conducted to assess content quality and direct relevance to the research objectives. This process removed 48 articles, including 29 articles on general sustainability finance without a specific digital integration focus, 12 studies on urban development without green finance emphasis, and 7 papers with insufficient depth on technology-finance integration mechanisms. A total of 33 articles were identified as relevant to form the dataset of the review. These 33 articles were selected based on their direct contribution to understanding the integration of digital technology in green finance structures for sustainable urban development. The final selection comprised articles explicitly addressing financing structures [such as revolving funds, public–private partnerships (PPPs), and green bonds] and their integration with digital innovations (including blockchain, AI, and digital platforms). These articles were then exported for bibliometric and content analysis.

2.3. Analysis

Analysis was conducted through two interconnected phases. A bibliometric analysis was conducted to understand global research trends and their impacts, including publication trends and geographical coverage. The researchers employed VOSViewer and Bibliometrix software (utilizing the R programming language, version 4.3.0) to analyze the data and generate visual networks that delineate the knowledge domain. Although alternative applications such as CiteSpace, Gephi, and Pajek provide analytical capabilities, VOSViewer was selected for its text processing functions and established use in finance research. The bibliometric analysis examined publication trends spanning 2013 to 2025. Geographic collaboration patterns were assessed through co-authorship. Keyword co-occurrence was analyzed with a minimum frequency threshold of two occurrences using the fractional counting method. This phase identified dominant research themes and provided a comprehensive overview of research trends, collaboration patterns, and conceptual structures in the field. Qualitative content analysis was conducted to enhance the bibliometric findings, facilitating thorough interpretation and identification of research gaps. This process began with initial open coding, conducted through a line-by-line examination of full texts, to identify key concepts related to financing structures and digital innovations. These concepts were then grouped into coherent themes through focused coding. Subsequently, they were synthesized into three dominant clusters that aligned with the bibliometric findings.

3. Results and discussion

This study's findings are presented in two sections. The first section presents a bibliometric analysis of the publication trends, keyword co-occurrence, and geographical origins of the dataset. The bibliometric analysis provides an overview of the research landscape, quantifying the growth, conceptual structure, and geographical distribution of literature on innovative green financing for

sustainable urban development. The second section provides a thematic content analysis of relevant articles, focusing on the central themes revealed by the bibliometric analysis.

3.1. Bibliometric analysis

3.1.1. Publication trend

As illustrated in Figure 1, the findings from the annual publication output indicate a significant increase in the number of articles since 2022, reflecting a surge of research interest in accordance with global policy advancements.

The initial publication relevant to this review was identified in 2013, signifying the inception of academic discourse on the financing of sustainable cities. Notably, no publications that met the inclusion criteria for this study were found between 2014 and 2017, suggesting a nascent and dormant phase in the field's development. This hiatus was broken in 2018 with the publication of two journal articles and one conference paper, indicating a pivotal phase in the advancement of the field. The subsequent years exhibited increasing momentum, with publications in 2020, 2022, and 2023, further reinforcing the research domain. In 2024, 14 published articles and two conference papers were identified, while 9 publications were recorded for 2025 (as of September 4, 2025). This upward trend indicates a growing significance of green financing for sustainable urban development in academic and policy discussions, solidifying the topic as a prominent area of research with substantial scholarly involvement. The field is thus regarded as rapidly advancing, with anticipated growth in interest in the forthcoming years. Subsequent sections provide a thorough analysis of the social and conceptual structures of this knowledge base.

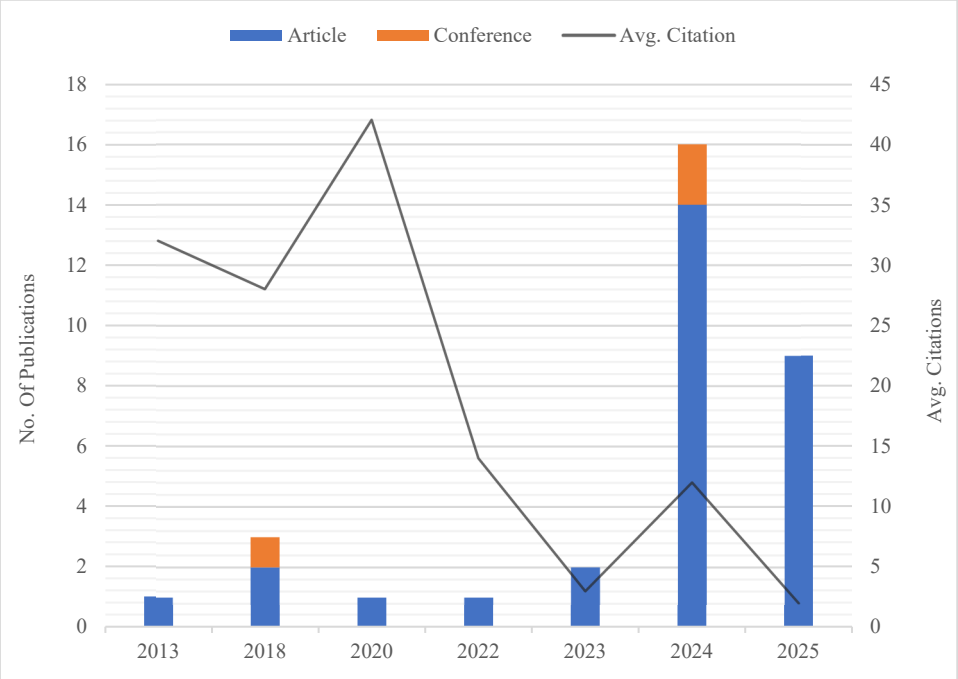

Figure 1. Annual publication and citation distribution (up to September 4, 2025).

3.1.2. Geographic collaboration of research publications

The geographical and collaborative structure of the field was further analyzed and visualized using Biblioshiny, as depicted in Figure 2. The map indicates that China serves as the primary center for collaborative clusters, engaging in global partnerships with countries including Australia, Cyprus, the Netherlands, Spain, South Africa, and the United Kingdom. Notably, a strong research partnership is evident between China and the U.K., as indicated by one of the thickest connecting lines. Spain also functioned as a crucial nexus, sustaining strong connections with Belgium, France, and South Korea.

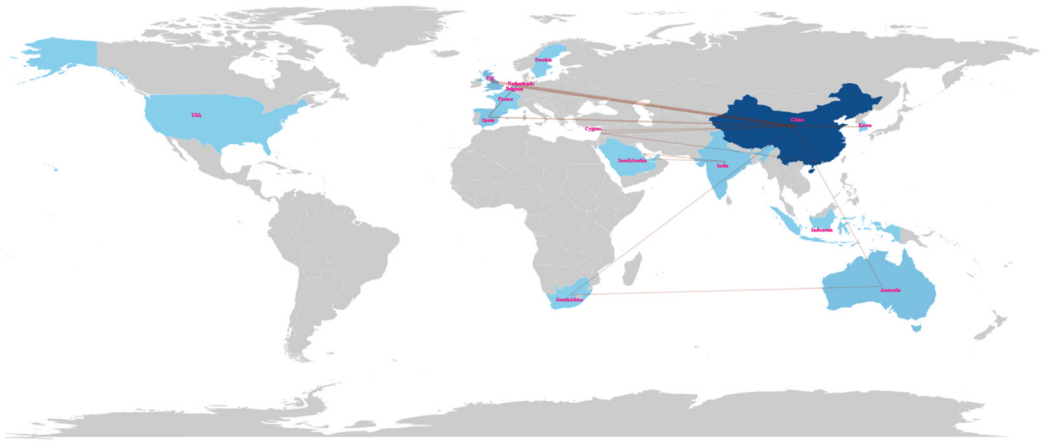

Figure 2. Countries' collaboration map of research publications.

Table 1. Collaborating countries.

S/N	Country	Documents	Citations	Total link strength
1	China	22	321	12
2	United Kingdom	4	45	2
3	Australia	3	17	3
4	India	2	3	2
5	Spain	2	19	5
6	United States	2	10	3
7	Austria	1	1	3
8	Bahrain	1	0	2
9	Belgium	1	8	3
10	Cyprus	1	42	1
11	France	1	8	3
12	Hong Kong	1	29	3
13	Indonesia	1	1	0
14	Japan	1	29	3
15	Lebanon	1	29	3
16	Netherlands	1	72	1
17	Saudi Arabia	1	2	0
18	South Africa	1	1	3
19	South Korea	1	11	2
20	Sweden	1	12	0
21	United Arab Emirates	1	0	2

Table 1 delineates the specifics of the 21 collaborating countries identified in the dataset through a co-authorship analysis conducted in VOSViewer. The unit of analysis was set to "countries", and the full counting method was employed. Table 1 confirms the central role of China, having the highest number of publications at 22, with 321 citations and a total link strength of 12. The analysis highlights prevailing collaboration patterns among some countries or regions while also exposing a highly clustered and uneven global research landscape, indicating a substantial gap that requires addressing.

3.1.3. Co-occurrence of keywords

A network was established to analyze the co-occurrence of keywords based on bibliographic data gathered. The VOSViewer software was configured to analyze "all keywords", employing the fractional counting method to guarantee an equal contribution from each article to the network as shown in Figures 3a and 3b). The minimum frequency of keyword occurrences was set at 2, with 65 of the 328 keywords meeting this threshold.

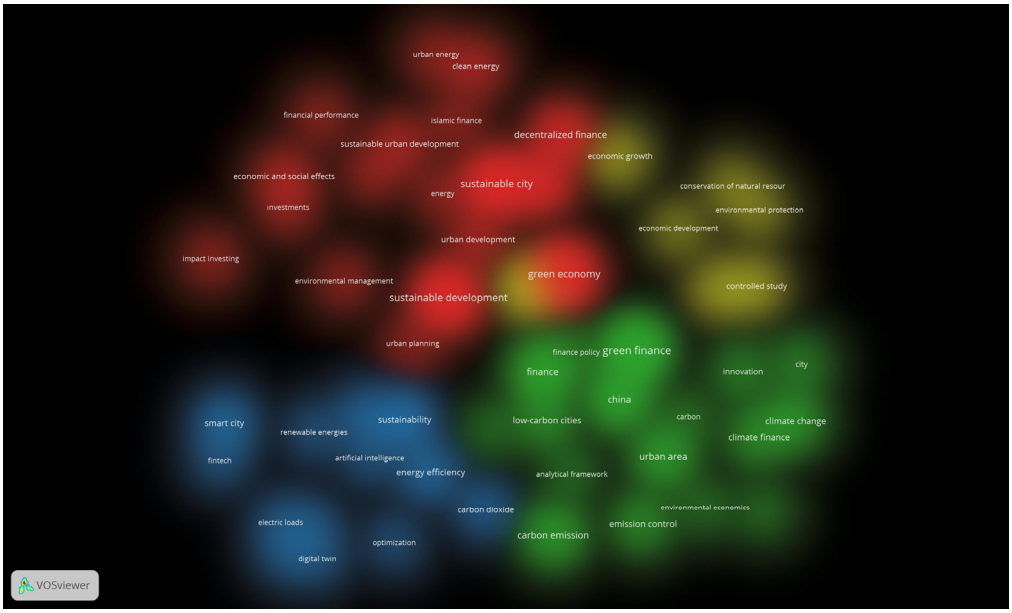

Figure 3a. Co-occurrence map of keywords.

Figures 3a and 3b illustrate the primary conceptual themes and their relationships in innovative green financing research for sustainable urban development. It signifies the focus of the main concepts in interconnected clusters, which constitute the fundamental intellectual themes within the research domain.

Four clusters were identified in the analysis, which were subsequently reduced to three by merging two clusters due to thematic overlap. These clusters were as follows: 1) the role of innovative green finance in government initiatives for sustainable urban development, 2) climate finance policies and institutional frameworks for low-carbon urbanization, and 3) green financing initiatives and digital innovations for sustainable smart cities.

The outlined clusters provided a framework for further content analysis of the prevailing topics in innovative green finance for urban development domain. The next section provides a brief introduction to the clusters.

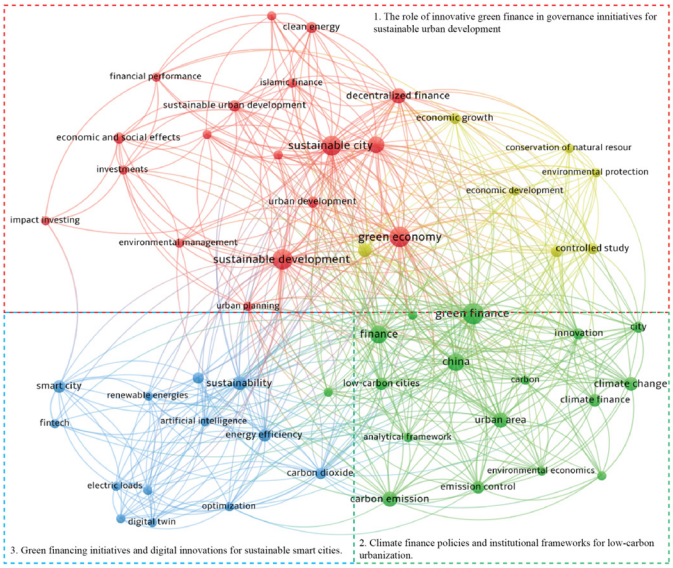

Figure 3b. Co-occurrence map of keywords.

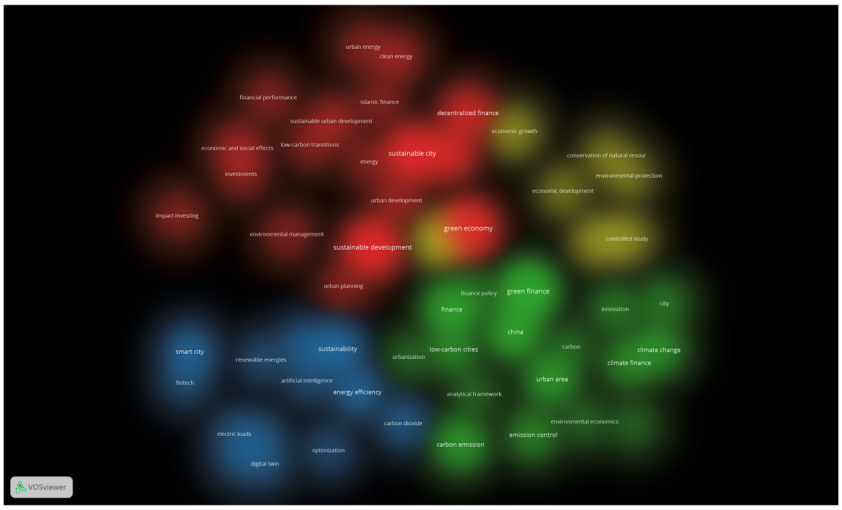

Figure 4. Density visualization of keyword clusters.

Cluster analysis

Cluster 1 (red and yellow): This cluster combines two clusters obtained from the keyword co-occurrence analysis (See Figure 4). The clusters share fundamental themes of sustainable development, urban transitions, resource conservation, and government mechanisms (e.g., urban planning, urban development, environmental protection, and environmental management), leading to the decision to merge them into a single cluster. Moreover, the red cluster highlights financial instruments (impact investing, Islamic finance, and decentralized finance), underscoring their increasing importance in the academic domain. Combining these clusters into a single cluster reflects the practical and institutional mechanisms that facilitate the transition toward sustainable urban development through innovative financing and policy integration. It emphasizes the significant role of innovative green financing within government initiatives aimed at sustainable urban development.

Cluster 2 (green): The keywords in this cluster highlight the importance of climate-related finance policies (e.g., climate finance, green finance, finance policy) in addressing climate change (e.g., emission control, carbon emissions, low-carbon cities) at all levels (e.g., urbanization, urban areas, China). China's significant presence signifies its global leadership in the development and implementation of green finance policy. China's significant presence in the cluster keywords indicates its global leadership in the formulation and implementation of green finance as well as sustainable urban development policies. It also underscores the need for research focused on rapidly developing economies, where policies and institutional frameworks are essential for sustainability. This cluster signifies that achieving low-carbon cities requires policy solutions, encompassing environmental and financial policies.

Cluster 3 (blue): The keywords from this cluster integrate critical technologies (e.g., artificial intelligence, digital twin, smart grid) and financing instruments (e.g., green bond, public-private partnership) for building sustainable smart cities. This can be interpreted in two ways: first, advanced technological solutions are essential for urban sustainability and necessitate innovative green financing, as the use of these technologies in urban development facilitates optimization and energy efficiency, resulting in decreased carbon emissions. Second, there is a need for digital innovation in green financing initiatives, as they can provide the necessary tools and platforms to support sustainable transition projects. By harnessing the power of technologies such as blockchain, for instance, stakeholders can enhance transparency and attract investment in eco-friendly ventures, ultimately driving progress toward a greener future.

Toward a synergistic framework for sustainable urban development

The analysis of the thematic clusters identified three primary drivers of sustainable urban development: government, green finance, and technology. Sustainable urban transitions are thus propelled by the potent synergy among governmental policies (which establish the vision and regulations), green finance (which supplies the resources), and technology (which offers the solutions). The conceptual framework in Figure 5 illustrates the interconnected roles of these three elements in transitioning toward sustainable urban futures.

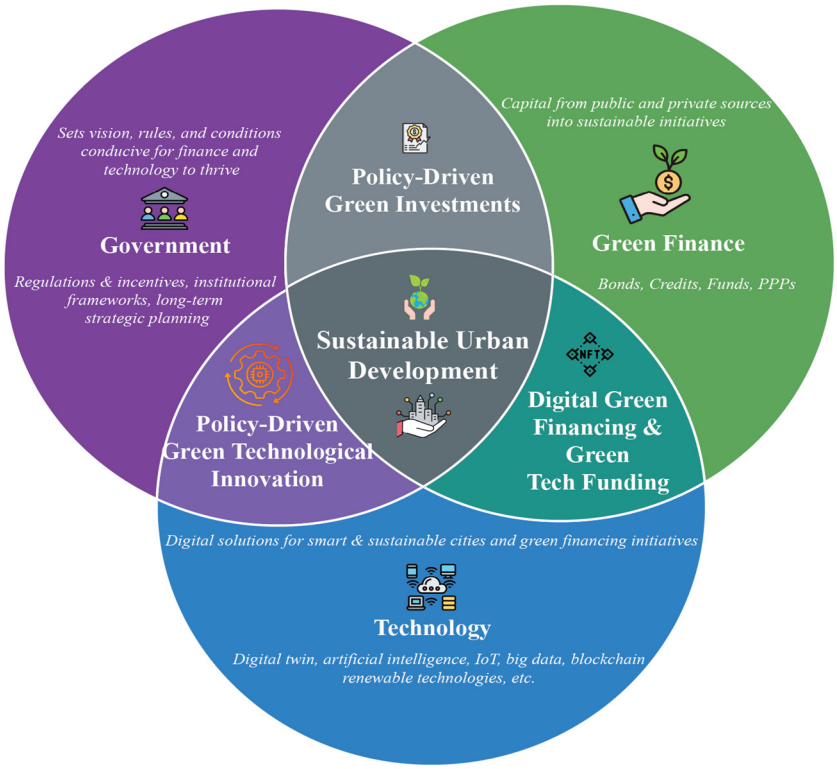

Figure 5. Conceptual framework for sustainable urban development.

Figure 5 depicts the interconnections among the three elements that facilitate sustainable urban development. The role played by each part is essential for achieving the overarching development goal, and thus, the true power of this triad lies in its interactive loops.

The government functions as the policymaker, with each policy it establishes directly influencing the market and fostering innovation. Governments formulate green credit regulations, develop green bond standards, and establish specialized institutions to promote green technology innovation and sustainable development. An exemplary case is China's Green Finance Reform and Innovation Pilot Zones, a policy aimed at effectively mobilizing capital and fostering innovation in renewable energy technologies (Yan et al., 2022; Zhang et al., 2023).

Green financing initiatives, on the other hand, alleviate the funding constraints that often hinder high-risk, long-term technological innovation as well as government initiatives for sustainable development. They therefore deploy finances from various sources, including public and private entities, to support innovations for sustainable urban development projects. For instance, green bonds and public–private partnerships have been identified as crucial in financing pilot smart city projects, as per the literature reviewed (Ma et al., 2024).

The role of digital technologies in today's rapidly evolving landscape cannot be overstated. Digital technologies provide effective solutions for sustainable transitions, turning financial capital into tangible, low-carbon assets and systems to fulfil sustainability goals. Digital technologies and financing initiatives are therefore in a constant cycle of interaction, as their advancement and deployment are crucial to sustainable development. Institutions also consistently devise digital solutions for financing initiatives to promote autonomy and transparency, thereby mitigating investment risks and attracting increased capital. Moreover, technology and finance facilitate the formulation of data-driven policies by utilizing data from

green initiatives to create more accurate and effective strategies. The synergy among these three fundamental pillars yields tangible urban sustainability outcomes, including enhanced energy efficiency, resilient infrastructure, and low-carbon, smart cities.

4. Discussion

The 33 reviewed articles provide varied evidence on the integration of digital green finance. The sample includes empirical policy analyses (primarily from China), technical feasibility studies on blockchain and tokenization, and case studies of project implementations. Studies consistently report that digital innovations can enhance transparency and broaden investment access. However, they also identify persistent barriers, including regulatory uncertainty, infrastructure limitations, and scalability concerns. The following sections analyze these findings across the core thematic areas identified from bibliometric clustering.

4.1. The role of innovative green finance in government initiatives for sustainable urban development

Attaining sustainable futures necessitates collaborative efforts, climate equity, and tailored policies that address the distinct challenges encountered by various communities. As a result, nations like China have formulated targeted regulatory approaches aimed at reducing carbon emissions while fostering economic development (Li et al., 2025). Research by Tan et al. (2025) and Tang and Huang (2024) highlighted the essential role of these regulations in enabling sustainable urban transitions through effective policy frameworks that encourage innovation and resource efficiency. These strategies, however, require innovative financing initiatives to ensure their successful implementation and scalability. Attracting investments that conform to policies and enhance long-term resilience through available financial instruments has thus received considerable attention in academic discourse.

This section examines how innovative green finance is promoting government policies and demonstration projects for sustainable urban development, as evidenced by the selected literature. The research primarily draws insights from China's demonstration projects and policies for urban energy transition and low-carbon cities. This analysis highlights the need for collaboration between the public and private sectors to achieve sustainability objectives.

4.1.1. Urban energy transition

Rapid urbanization often creates a surge in energy demands, making sustainable development critical for cities. This increasing energy demand in urban areas usually presents significant challenges, such as the depletion of natural resources and the deterioration of ecosystems from harmful emissions (Khan et al., 2022). Addressing these issues requires that governments formulate and execute strategies focused on prioritizing the adoption of renewable energy sources and optimizing energy management systems. One such strategy identified in the selected articles is energy transition policies, exemplified by China's New Energy Demonstration City (NEDC) Policy.

Urban energy transition has become an essential avenue for achieving sustainable development, especially in rapidly urbanized economies. The empirical analysis of China's NEDC policy offers valuable insights into how government-led initiatives can facilitate urban energy transformation and enhance sustainability (Tan et al., 2025). The NEDC policy is aimed at facilitating the adoption of

renewable energy, reorganizing urban energy infrastructure, and fostering green economic growth (Che et al., 2023). It urges local governments to tailor their energy strategies according to regional circumstances, thereby promoting decentralized innovation and stakeholder participation (Tan et al., 2025). The policy emphasizes adaptability, inclusivity, and alignment with local development goals, ensuring that energy initiatives address immediate needs while promoting long-term sustainability.

Tan et al. (2025) confirmed the efficacy of the NEDC policy in promoting urban sustainability, identifying three principal enablers: technological innovation, industrial upgrading, and development of green finance initiatives. The policy consequently encourages the establishment of provincial green finance institutions that formulate tailored investment strategies for renewable energy initiatives. Tang and Huang (2024) and Zeng and Zhang (2024) substantiated this claim, illustrating that green finance considerably advances urban energy efficiency in Chinese prefecture-level cities. This highlights how targeted government interventions, supported by innovative finance and technological advancements, can promote sustainable urban development.

4.1.2. Low-carbon cities

The low-carbon city pilot policy, initiated by the Chinese government in 2010, is a crucial initiative designed to combat climate change and decrease carbon emissions by developing and implementing repeatable low-carbon urban development models via pilot projects in designated cities (Gao et al., 2025). A low-carbon city is an urban area that implements coordinated policies and practices to reduce greenhouse gas emissions, particularly carbon dioxide, by improving energy efficiency, increasing the use of renewable energy, and developing sustainable infrastructure (Khanna et al., 2014). The inadequacy of current financial systems to tackle modern sustainability issues and climate change has highlighted the necessity of reassessing the role of finance in confronting these challenges (Zhan and de Jong, 2018). Both Gao et al. (2025) and Zhan and de Jong (2018) emphasized green finance as a driving force for low-carbon city development.

The results from Zhan and de Jong (2018) on the Shenzhen International Low Carbon City indicate a transition from conventional, unsustainable financing schemes to a diverse, innovative strategy that encompasses stakeholder-inclusive public–private partnerships, impact investing, and foreign investment. It also highlighted the essential function of government in establishing institutional frameworks and mitigating investment risks to foster conditions conducive to the effective operation of these financial mechanisms. The study also highlights the need for a collaborative approach to innovative finance and government policies, without which sustainable urban development initiatives are unlikely to realize their full potential. Stakeholder engagement is therefore paramount to an environment conducive to long-term success.

The success of government policies, therefore, increasingly hinges on the ability to devise innovative financial instruments that are both economically sustainable and actively generate social and environmental value, transcending conventional financing constraints toward a sustainable urban future.

4.2. Green finance initiatives for sustainable urban development

4.2.1. Revolving funds and financial engineering

A revolving fund is an emergent financial innovation that can facilitate sustainable urban development. Revolving is a self-replenishing financial instrument established by an agency, institution, or body for specific objectives, such as energy retrofitting of existing buildings, energy efficiency, or climate adaptation (Gouldson et al., 2015). It is a dedicated pool of funds that is replenished by interest and principal repayments. The European Union's (EU) Joint European Support for Sustainable Investment in City Areas (JESSICA) serves as a classic example of a revolving fund for sustainable urban development. The initiative channels funds provided by the EU into a holding that provides loans, guarantees, and equities specifically for city regeneration projects.

In lieu of a one-off grant, JESSICA provides long-term loans and equity capital whose repayment is channeled into new projects. This creates a self-sustaining pool of funds. Unlike conventional grants, which are exhausted upon expenditure, capital from repaid loans is returned to the fund and can be lent out to another borrower. Thus, a single initial capital can fund multiple successive projects (Nadler, 2018).

4.2.2. Green public-private partnerships (PPPs)

PPPs have become a crucial mechanism for managing the financing and scheduling of sustainable urban development technologies and projects, including smart city energy initiatives (Ma et al., 2024; Xu and Xu, 2024). As the need for innovative solutions to urban challenges increases, the significance of PPPs in promoting sustainability and urban resilience is expected to grow. PPPs are typically long-term agreements and collaborations between a government authority and a private organization aimed at financing, constructing, and operating public infrastructure effectively while utilizing diverse resources and expertise.

This mechanism is being advocated as a means of funding end-user technologies and the digital infrastructure necessary for operating smart cities. For instance, Xu and Xu (2024) examined and explicitly modeled the financing of smart grid and solar-battery projects for smart cities through green bonds and PPPs, illustrating the direct application of these financial instruments in achieving urban sustainability objectives. Ma et al. (2024) also emphasized the significance of PPPs and green bonds as financial instruments for smart city infrastructure, focusing on a cloud-fog computing framework to manage data flow from a net-zero energy grid, thereby optimizing energy distribution and reducing power shortages. These strategies facilitate enhanced collaboration between the government and private sectors, drawing investment and expertise essential for the transition to a more sustainable urban future.

4.2.3. Digital innovations for green financing initiatives

Green digital financing mechanisms for sustainable urban development

Digital finance mechanisms wield an impressive prospect in advancing sustainable urban development. Empirical evidence from Li et al. (2022) indicates that the expansion of digital finance

mechanisms for green initiatives significantly influences environmental inequality. Digital finance mechanisms, such as mobile payments, mobile banking, and peer-to-peer digital lending platforms, expand credit access for firms to facilitate their transition to green technologies. Furthermore, integrated digital finance platforms allow financial institutions to incorporate environmental performance into lending decisions. Such actions could proportionately influence green compliance among firms responsible for urban development. Digital green finance structures can be used to significantly influence shifts in the consumer market. Incentives such as subsidies on loans for green solutions could facilitate investments in cleaner substitutes, such as electric transportation and renewable energy products, among households and businesses.

Digital finance can be pivotal to urban resilience and inclusivity. It creates an opportunity for sustainable urban development by providing the means required to ensure that cities and communities withstand, adapt, and recover from external shocks. Digital finance platforms such as e-wallets and mobile banking provide businesses and households with rapid access to liquidity during shocks like pandemics and natural disasters. Also, digital finance mechanisms and platforms significantly ensure the continuous functioning of smart city systems. Digital finance platforms provide integrated methods of payment for amenities such as transportation, energy consumption, and general utilities. This ensures that urban services are efficient and inclusive. Digital finance mechanisms are an essential source of capital for green transitioning in urban settlements and a key to sustainable consumption.

Aside from digital finance, other digital innovations have been integrated to restructure the pooling, management, and distribution of resources for green and sustainable outcomes. These emerging digital innovations decentralize and digitalize green finance within frameworks and agreements. These include blockchain and tokenization (the conversion of assets into digital tokens on a blockchain), artificial intelligence and big data, and the Internet of Things.

4.2.4. Blockchain and tokenization

Blockchain is emerging as a key facilitator of green financing in recent times. Its features of data immutability, decentralization, and cryptographic security are essential to the requirements of transparency and trustworthiness in green financing. In a blockchain, data from every transaction is recorded in a linked "block" distributed across a network (Kalaiarasi and Kirubahari, 2023). Data from new green finance transactions are cryptographically tied to previous ones; thus, the method ensures that the data is immutable. Data immutability in green finance is essential to prevent fraud and greenwashing. Additionally, blockchain could potentially eliminate instances of information asymmetry in a green financing scheme by making interactions and data transparent to all stakeholders (Schletz et al., 2020).

For instance, a self-executing blockchain-based smart contract would release and approve interim payments only when verifiable green milestones are attained. Research on JP Morgan's Quorum blockchain platform demonstrated a 70% reduction in settlement times through smart contract automation (Guo and Liu, 2025). This ensures that the conditions agreed in the contract are strictly adhered to and automatically enforced. Blockchain-based green finance systems ensure that all transactions are publicly verifiable.

An application of a blockchain-based green finance system is the tokenized securities for green investment. In a security token offering (STO), conventional assets such as bonds and equity stakes are represented as a digital token on a blockchain. Tokenization involves the fragmentation of large projects

into smaller units to allow retail investors to hold these units as assets. The Hong Kong government issued tokenized green bonds in February 2023 and February 2024, with the latter issuance worth approximately HK$6 billion, representing the world's first multi-currency digital bond offering (Broby and Yang, 2025). The success of these issuances was underpinned by clear regulatory frameworks and integration with existing market infrastructure. Though nascent, tokenization wields the potential to pool funds of significant magnitude for sustainable urban development. For example, significant funding could be pooled from retail and institutional funding sources for the development of a solar farm to facilitate green energy generation. Tokenized green bonds and equity can lower the barriers for small retail investors and businesses while expanding capital accessibility in developing markets.

Essentially, blockchain and tokenization establish transparency by making terms, clauses, and transactions publicly verifiable. The immutability and transparency of blockchain-based green financing boost investor confidence. Blockchain and tokenization also ensure disintermediation and the inclusion of a broad range of investors. The unique cryptographic identities assigned to investors eliminate reliance on a central authority and allow anyone to invest in green projects using a private key wallet. Blockchain's unique identity features facilitate peer-to-peer transactions with superior security at a lower cost (Dorfleitner and Braun, 2019). In effect, substantial funding for environmental and climate projects can be raised from new investor segments untapped by the current market, thereby expanding the funding pool. However, widespread adoption faces notable challenges. Regulatory uncertainty in many jurisdictions creates compliance risks, as legal frameworks governing tokenized securities remain underdeveloped. Technical constraints such as scalability limitations and energy consumption concerns also hinder implementation (Broby and Yang, 2025).

4.2.5. Big data and AI analytics

The large heterogeneous data produced from green finance databases and stakeholders benefit immensely from large-data analytics and machine learning to identify trends and latent patterns that are key to decision-making and efficiency. These large heterogeneous data, known as big data, can improve risk management and impact measurement in green finance. AI algorithms can be used to analyze these data to streamline processes, bridge the information gap between investors and green projects, and enhance the accuracy of evaluation (Xiao et al., 2024). For instance, AI algorithms can be used on big green data to identify and screen potential green bonds for compliance with environmental standards.

Recently, AI-powered tools have demonstrated promise in personalizing sustainable investments and detecting climatic risks. AI tools have been used to analyze unstructured information to generate investor portfolios that align with sustainability expectations (Shkodina, 2024). AI models have also been utilized to predict market trends and develop knowledge-based environment-aligned roadmaps (Elouidani and Outouzzalt, 2023). With energy conservation, AI has demonstrated promise in optimizing grid operations and renewable energy forecasting. This facilitates green financing by validating green projects' bankability with verifiable data.

Green financing stands to directly benefit from AI. AI-driven credit scores have the potential to reduce default rates on green bonds by comprehensively analyzing and accurately pricing climate risk. Machine learning models can analyze alternative data sources to assess creditworthiness when traditional credit histories are unavailable. For instance, Berg et al. (2020) found that digital footprint variables complemented traditional credit scores, improving predictive accuracy by 5.3 percentage

points. The effectiveness of AI in green finance depends largely on robust data infrastructure and technical capacity within financial institutions. Organizations with well-developed data management systems can leverage machine learning more effectively for credit assessment and portfolio optimization. AI also facilitates more efficient and credible verification of emission reductions, eliminating the likelihood of double-counting by cross-checking independent data streams. Though still in its infantile stages, AI-driven big data analytics can significantly improve the efficiency of the management of green investments.

4.2.6. Integrating digital innovations into green finance initiatives

Digital finance mechanisms, including blockchain, tokenization, big data, and AI, are facilitators of green finance initiatives. They facilitate the efficiency and accuracy of decision-making, improve stakeholder engagements, and help demonstrate transparency. Utilizing these digital innovations within the revolving fund and green public–private partnership (PPP) frameworks of green finance initiatives holds substantial potential to reshape sustainable urban development.

For revolving funds, blockchain and tokenization can be used to establish smart contracts and democratize the pooling of funds to be distributed by a firm or an institution for green projects (Guo and Liu, 2025). The smart contract established on a blockchain such as Ethereum defines the parameters of a green project and encodes the project conditions into the contract for decentralized transparency. The firms can issue security tokens, representing ownership of a portion of the project, to be purchased by retail and institutional investors, as well as the general public (Broby and Yang, 2025). This ensures a democratized participation. Upon purchase of tokens, the smart contract automatically transfers their funds to the electronic revolving pool wallet. The disbursement and use of the funds are immutably recorded, stored, and tracked on the blockchain.

Smart verification tools integrated into the smart contract can be used to govern the execution of the green project. These smart verification tools verify and trigger the smart contract to issue and record payments when performance thresholds are achieved. Repayment of funds is made into the smart contract wallet. Stakeholders are automatically updated via token holders' dashboards and are informed about the recalculated capital available. The use of blockchain and tokens in revolving funding significantly improves transparency and accountability.

Green PPP (GPPP) involves multiple stakeholders from diverse backgrounds. Thus, leveraging digital innovation enhances the execution of GPPP in many ways. First, similar to revolving funds, an integrated IoT blockchain can be used to develop and administer smart contracts governing GPPP projects (Alnahari and Ariaratnam, 2022). An integrated IoT blockchain verifies work done in real-time and triggers smart contracts to release interim payments when milestones are reached. This process expedites project execution, reducing stakeholder disputes and administrative bottlenecks.

Additionally, enormous heterogeneous data, such as urban traffic, rates of carbon emissions and absorption, population demographics, and density, can be collected as big data. AI can be used to analyze big data to identify the sustainable development requirements of a selected population in an urban setting (Bibri et al., 2023). This is essential for developing streamlined solutions that are consolidated at green projects for execution. In a GPPP agreement, AI can be used to analyze the capacity of contractors based on previous records, including their creditworthiness and adherence to green policies and expectations (Berg et al., 2020). This ensures that the right contractors with capacity and expertise in executing projects with green objectives are selected.

Digital finance mechanisms can be crucial to GPPP. First, green digital platforms serve as an online marketplace that connects public institutions to green financiers. These digital platforms allow public institutions access to a broad base of potential sources of finance for green projects. These include financiers, such as small and medium-scale enterprises, institutional and retail investors, and private individuals, which were previously not considered in PPP agreements. An integrated tokenized-blockchain-based digital finance platform democratizes the GPPP and enlarges the funding pool. Large-scale green projects can be disintegrated into smaller units of investment, with each unit being represented by a token. These tokens can be purchased by SMEs, institutional and retail investors, and private individuals to raise funding for the execution of the project. In such a GPPP, the public sector guarantees project legitimacy and administers the project. The institutions and individuals fund the project and share its returns; the private party to the partnership executes and operates the green project.

Though revolving funds and GPPP are innovative green finance structures, digital innovation can be used to maximize the benefits from their intersection. For example, an integrated AI-tokenized-blockchain-based digital finance platform can be used by a public institution to raise significant funding from a broad base of private and individual investors for green projects (this highlights the GPPP aspect). The public institution then converts the funds raised into green bonds to be issued via smart contracts to projects providing green solutions. These green bonds are to be repaid within a specific period of time and reinvested into another green project (this highlights the revolving fund aspect).

Undoubtedly, digital innovations are essential and transform the very fiber of green finance initiatives. They broaden the base for fund pooling, automate the flow of funds and information, provide security, efficiency, and transparency, and ensure sustained urban development. The integrated use of the digital innovations highlighted in GPPP and revolving funds can help to address funding shortfalls for green projects and initiatives.

5. Conclusions

This study presents a systematic review of 33 relevant articles on green finance models for sustainable urban development, sourced from the Scopus database. Bibliometrics and content analysis were the two key methods employed, which revealed the conceptual and intellectual structures of the research domain. The analysis of document numbers and collaboration networks revealed that China serves as the dominant research hub with 22 publications and extensive international partnerships, while South America and Africa were the continents with little to no research works on digital green finance integration for urban sustainability. The topmost green finance structures identified to be facilitating sustainable urban development include revolving funds, green public–private partnerships, green bonds, and sustainability-linked debt. Pertinent digital innovations enhancing these finance mechanisms include blockchain and tokenization, artificial intelligence and big data analytics, digital finance platforms, and the Internet of Things, which significantly improve transparency, democratize investment participation, and optimize resource allocation.

The reviewed studies highlighted the necessity of smart contracts and tokenized platforms to automate compliance monitoring and enhance investor participation. This would help ensure environmental accountability and mitigate greenwashing concerns in sustainable projects. Gaining insight into these digital solutions would help prevent costly implementation errors and attract a wider range of capital from both retail and institutional investors. These findings can inform policy

formulation and institutional frameworks, facilitating the adoption of appropriate technologies for green finance optimization. The findings have significant implications for urban planners and policymakers who will need to understand how to harness digital innovations effectively to meet sustainability targets in rapidly urbanizing areas.

This research makes distinct contributions to theory, policy, and practice. Theoretically, it advances understanding of how digital technologies transform traditional green finance structures. The synthesis establishes linkages between technological capabilities (blockchain, AI, digital platforms) and financing mechanisms for urban sustainability. This provides a conceptual foundation for future research in this emerging field. For policy, the study identifies regulatory clarity and standardization as critical success factors. Policymakers can use these insights to design frameworks that balance innovation with investor protection. The study identified the need for governments to establish regulatory sandboxes for tokenized green securities, following models like China's Green Finance Pilot Zones. Standardized smart contract templates for green bonds and PPP agreements are needed to reduce implementation barriers. Public investment in digital infrastructure capacity, particularly blockchain nodes and AI analytics systems, is essential for effective oversight. Additionally, international coordination should focus on developing cross-border standards for tokenized green assets to facilitate capital flow to developing markets facing the $2.7 trillion infrastructure gap. Practitioners, financial institutions, and project developers can apply the findings to implement digital innovations in their green finance operations. The identification of barriers such as infrastructure gaps, technical constraints, and market acceptance challenges enables practitioners to develop targeted adoption strategies.

This study has limitations worthy of noting, despite its significant contributions. The study exclusively derived its dataset from the Scopus database. A potential exploration of a combination of other scholarly databases, such as Web of Science, may yield further intellectual relationships and insights within the field in the future. The literature sample included in the study was confined to peer-reviewed publications and conference papers, eliminating book chapters and industry reports. Consequently, future research employing these supplementary reference materials is recommended to uncover gaps and compare academic literature with industrial practices. Finally, future studies are encouraged to validate the findings with case studies of actual projects, gather comprehensive empirical data from financial institutions and technology providers, and test the proposed framework across diverse economic and regulatory environments to establish its applicability and effectiveness.

Author contributions

All authors have participated in the Conceptualization, Investigation, Methodology, Formal analysis, Writing, Reviewing, and Editing of the research paper.

Use of AI tools declaration

The Authors confirm that the manuscript has been created by themselves and no AI tool/Large Language Model (LLM) has been used.

Conflict of interest

The authors declare no conflict of interest.

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