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Digital Technologies Research and Applications
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Review

Click, Store, Emit: The Environmental Cost of Digital Infrastructure

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Received: 7 July 2025; **Revised:** 20 July 2025; **Accepted:** 29 July 2025; **Published:** 20 August 2025

Abstract: The accelerating expansion of digital infrastructure, including data centers, communication networks, and Artificial Intelligence (AI) systems, is transforming economies and societies worldwide. However, this digital transformation carries a growing environmental cost, particularly in terms of carbon emissions, resource consumption, and lifecycle waste. This literature review critically explores the environmental footprint of digital infrastructure, with a primary focus on carbon emissions across the stages of manufacturing, operation, and disposal. While studies from China dominate the empirical base due to its rapid digitalization, the review incorporates comparative evidence from Europe and North America to strengthen its global applicability. Key sources of emissions are identified in energy-intensive operations such as data center cooling and AI model training. To mitigate these impacts, this study examines integrated strategies including renewable energy deployment, nanotechnology-based cooling innovations, Environmental, Social, and Governance-driven policy frameworks, and circular economy applications. A revised research framework is proposed to guide future investigation into sustainable digitalization. Moreover, this review emphasizes the importance of public participation in smart city governance, advocating for co-created urban solutions, open data platforms, and inclusive digital planning. By embedding solution pathways throughout the discussion, the paper presents a cohesive analysis that bridges technological innovation with climate and environmental priorities. Ultimately, this concludes with recommendations for cross-sectoral collaboration among governments, industries, and communities to ensure that digital progress aligns with long-term sustainability goals.

Keywords: Digital Infrastructure; Carbon Emissions; Smart Cities; Environmental Governance; Renewable Energy; Public Engagement

1. Introduction

The global expansion of digital infrastructure has become a defining feature of contemporary society, underpinning economic growth, social connectivity, and technological advancement. From data centers and cloud computing platforms to artificial intelligence systems and pervasive internet access, digital infrastructure enables the seamless functioning of industries and everyday life. However, the environmental consequences of this rapid digitalization remain insufficiently examined, particularly the carbon emissions embedded across the infrastructure's lifecycle stages, including construction, operation, maintenance, and disposal [1].

Current discourse often frames digital technologies as enablers of sustainability, emphasizing their potential to optimize systems, reducing resource consumption, and facilitating low-carbon transitions [2]. Yet, this perspective frequently overlooks the energy-intensive nature of digital infrastructure itself, which relies heavily on electricity derived from fossil fuels, contributing significantly to greenhouse gas emissions. Data centers alone consume an estimated 20% of global electricity, with projections indicating substantial increases due to the growing demand for cloud services, high-performance computing, and large-scale machine learning models [3]. Moreover, the production of digital hardware, including servers, networking equipment, and cooling systems, incurs substantial carbon emissions, which are often excluded from environmental impact assessments.

Emerging research underscores the spatial variability of these emissions, demonstrating that the carbon footprint of digital infrastructure is shaped by regional energy mixes, technological efficiencies, and user behavior. Policies such as "Smart Cities" and "Broadband China" illustrate how digital infrastructure can contribute to emissions reductions when coupled with renewable energy integration, energy-efficient practices, and robust environmental governance. However, inconsistencies in carbon accounting methodologies and the absence of comprehensive lifecycle analyses hinder the accurate assessment of digital systems' environmental impacts.

This review contributes to the growing discourse on sustainable digitalization by providing a comprehensive and lifecycle-based synthesis of the environmental impacts of digital infrastructure. Unlike prior reviews that focus narrowly on either data centers or cloud services, this paper expands the lens to include the full ecosystem of digital infrastructure, encompassing construction, operation, AI applications, user behavior, and post-use emissions. It also introduces recent evidence on how emerging strategies such as digital twins, nanotechnology, and Environmental, Social, and Governance (ESG)-linked investments are transforming digital systems from emission sources into potential enablers of environmental sustainability. By identifying critical gaps in emission accounting and emphasizing behavioral and policy-level interventions, this review offers a framework for aligning digital infrastructure growth with climate mitigation goals. The remainder of the article is structured as follows: Section 2 outlines the methodology used to select and organize the reviewed literature. Section 3 examines the carbon footprint of digital infrastructure, particularly within urban systems. Section 4 focuses on the role of artificial intelligence and digital twins in reducing emissions. Section 5 explores how social media use and user behavior contribute to digital carbon footprints. Section 6 addresses the broader environmental implications of digitalization. Finally, Section 7 concludes the paper by summarizing key findings, identifying limitations, and proposing future research and policy directions.

2. Methodology

2.1. Search Strategy

This literature review followed a structured search strategy to ensure systematic identification and selection of relevant peer-reviewed sources. Search was conducted using two platforms: Google Scholar and ResearchGate, chosen for their accessibility and wide indexing of environmental science, sustainability, and digital technology literature. To refine the search process, the following Boolean search strings were used in varying combinations: "carbon emissions" AND "digital infrastructure," "data centers" AND "climate impact," "digital transformation" AND "urban pollution," "AI" AND "carbon footprint," "green innovation" AND "ICT," "sustainability" AND "smart cities" AND "China," and "ESG" AND "digital infrastructure."

The search was conducted to include only articles published between 2010 and 2025. This time window was selected because it captures the acceleration in digital infrastructure investments, the emergence of AI and digital twin applications in sustainability, and the surge in policy-driven ESG practices, particularly in urban and Chinese contexts.

2.2. Inclusion and Exclusion Criteria

To ensure consistency, the following inclusion criteria were applied:

- Articles published in peer-reviewed journals or high-quality conference proceedings
- Publications written in English
- Empirical or review studies directly addressing the environmental or climate impact of digital infrastructure
- Studies discussing mitigation strategies such as energy efficiency, AI optimization, renewable integration, or ESG-based performance models
- Geographic focus on urban systems or national frameworks, with priority given to China and countries involved

in smart city or digital economy strategies

Exclusion criteria included:

- Studies focusing solely on social or economic impacts without environmental context
- Editorials, opinion pieces, or grey literature
- Duplicate records retrieved across both databases
- Papers lacking methodological clarity or empirical evidence

2.3. PRISMA Diagram

The article selection process was guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. **Figure 1** outlines the flow of records through the identification, screening, eligibility, and inclusion phases.

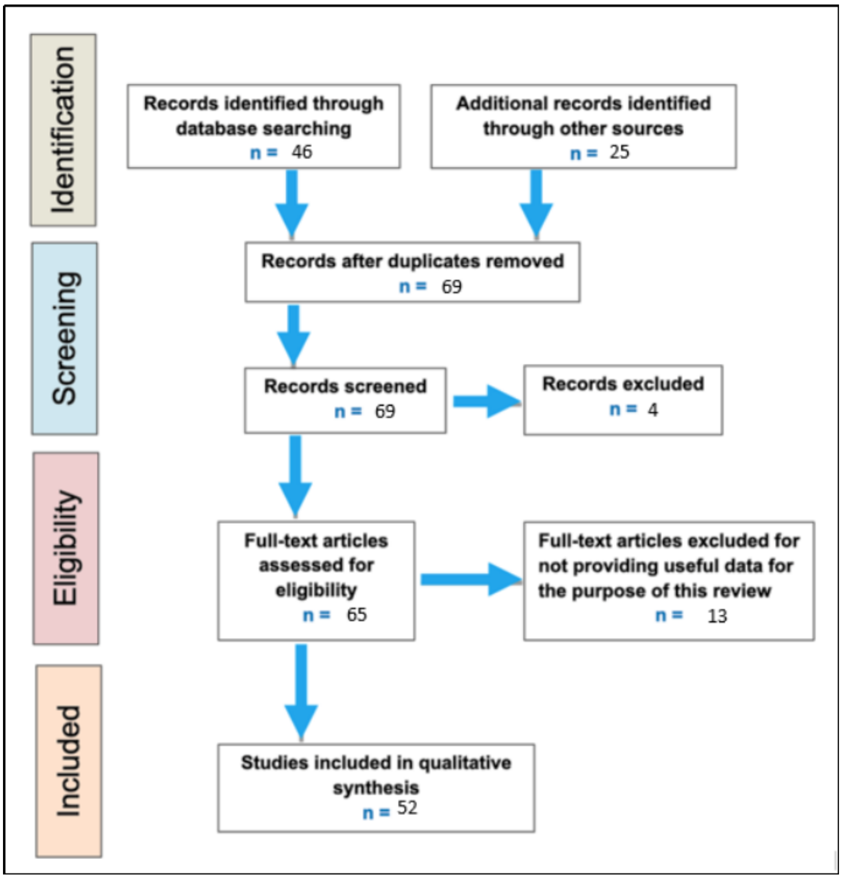

Figure 1. PRISMA Representation Diagram by the Authors.

Following article selection, each study was coded for key variables including publication year, geographic scope, digital infrastructure type (e.g., AI systems, data centers, IoT, platforms), and reported environmental outcomes (e.g., carbon emissions, air pollution, resource efficiency). Based on recurring patterns, the literature was grouped thematically into six primary domains:

1. Carbon impacts of digital infrastructure development
2. Urban systems and regional disparities
3. Artificial intelligence and computational intensity
4. Behavioral contributions to the digital carbon footprint

5. ESG-linked performance and governance strategies
6. Green mitigation technologies and sustainability frameworks

This thematic organization supported the synthesis structure presented in the results and discussion sections that follow.

2.4. Research Framework

To guide this review, a conceptual research framework was developed (**Figure 2**). It outlines the environmental impacts of digital infrastructure across its lifecycle and highlights the contributing factors, mitigation strategies, and policy implications. This framework informed the thematic analysis and helped structure the findings presented in the following sections.

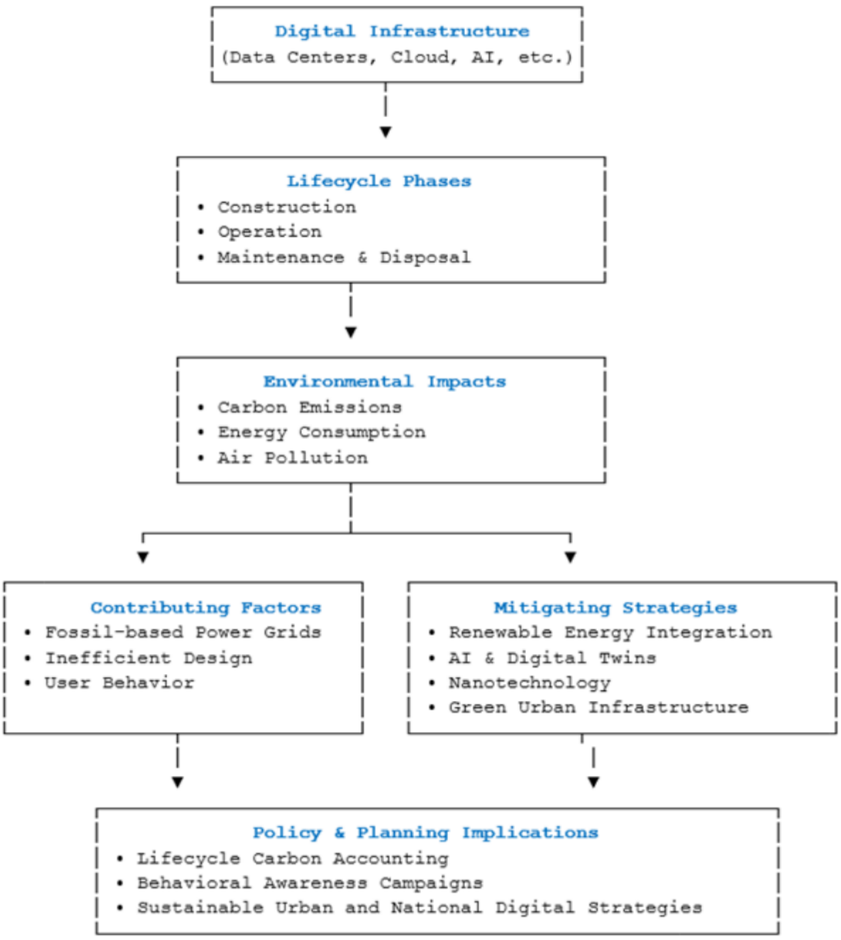

Figure 2. The Research Framework in This Review.

3. Impact of Digital Infrastructure on Urban Carbon Emissions

Understanding the environmental implications of digital infrastructure necessitates anchoring its carbon footprint within a broader spatial framework. Recent literature emphasizes that carbon emissions must be examined not only as isolated outputs of energy consumption but also as the product of systemic, spatially differentiated dynamics. Studies at the global, regional, and local levels offer converging insights into the structural and spatial factors shaping emission patterns, many of which intersect directly with the digital transformation of urban and industrial systems.

At the global level, Liu et al. (2023) reported that in 2022, global CO_2 emissions rose by 1.5% compared to 2021, and by 7.9% and 2.0% relative to 2020 and 2019, respectively, reaching a total of 36.1 gigatons [4]. These emissions accounted for approximately 13% to 36% of the remaining carbon budget required to limit global warming to 1.5 °C, indicating that this threshold could be exceeded within the next 2 to 7 years if current trends persist [4]. Besides, Freitag et al. (2021) argued for a fundamental shift in how decarbonization is conceptualized, moving beyond national emission inventories toward a systems-based understanding of carbon responsibility. Their analysis highlights how consumption in one region often leads to emissions in another, particularly within digital value chains [5]. As cloud computing, artificial intelligence, and digital platforms continue to expand, the associated emissions are frequently outsourced to countries where data centers and digital infrastructure are powered by fossil-based energy systems. This dislocation of carbon responsibility complicates mitigation efforts and underscores the importance of including digital infrastructure in global carbon accounting frameworks. The authors further stress that effective climate strategies must acknowledge the embeddedness of digital infrastructure within global trade, finance, and technological networks, where decarbonization efforts in one domain may be undermined by emissions leakage in another [5].

At the regional level, Labzovskii et al. (2019) evaluate the effectiveness of national environmental policies in reducing fossil fuel carbon dioxide emissions across East Asia, despite widespread submission of Nationally Determined Contributions (NDCs) [6]. Focusing on China, Japan, South Korea, and Mongolia, the analysis shows that flagship policies implemented in the 2010s contributed to slowing $FFCO_2$ growth rates—by 1% in South Korea, 5% in Mongolia, 8% in China, and a decline in Japan. Among these, China's 12th Five-Year Plan (2011–2015) had the most substantial impact, aligning with the region's lowest $FFCO_2$ growth rates, driven by reductions in coal consumption, cement production, and overall emissions. Future projections comparing policy-on versus policy-off scenarios show that policies significantly reduce emissions: 24%, 80%, and 166% reductions by 2020, 2025, and 2030, respectively. However, these reductions still fall short of NDC targets. By 2030, even under a policy-on scenario, Japan, South Korea, and Mongolia would not fully meet their pledged goals. China's compliance remains unassessed due to the absence of economy-independent targets, though Eastern provinces are expected to remain the country's main emitters. The study concludes that while national policies help mitigate emissions, they are insufficient without a supranational framework to ensure effective regional coordination and compliance with global climate agreements [6].

Zooming in further, Dou et al. (2021) examined the carbon footprints of Hong Kong and Macao, two highly urbanized regions characterized by their dependency on external sources for energy and material resources [7]. Their study assessed emissions across three scopes: direct emissions from local fuel combustion (Scope 1), emissions from imported electricity (Scope 2), and embodied emissions from traded goods and services (Scope 3). The analysis revealed that in 2018, Scope 1 emissions in both cities stabilized at approximately 50 Mt, representing only 0.6% of China's total emissions. However, when Scope 3 emissions were included, the total carbon footprints of Hong Kong and Macao were nearly three times greater, with significant growth observed between 2000 and 2015. This increase was largely attributed to unfavorable trade balances and the rising carbon intensity of imports. The authors further emphasized that focusing solely on Scope 1 emissions leads to a significant underestimation of these cities' climate responsibilities. They recommended that mitigation policies be expanded to account for outsourced emissions embedded in global supply chains, particularly given the consumption-driven nature of both economies [7].

Besides, Xia et al. (2025) developed a high-resolution carbon dioxide emission inventory for East Asia, recognizing the critical need for spatially detailed data to support effective emissions assessment and management developed a high-resolution carbon dioxide emission inventory for East Asia, recognizing the critical need for spatially detailed data to support effective emissions assessment and management [8]. Employing a top-down spatial proxy model at a 1 km resolution, their study covered the period from 2012 to 2021 and integrated multiple datasets using geographically weighted regression techniques [8]. This methodological approach aimed to enhance the spatial accuracy of sectoral emission estimates across diverse urban and industrial landscapes. To validate their inventory, the authors compared their results with established bottom-up datasets, including the Multi-resolution Emission Inventory for China (MEIC), and found a broad convergence in emission patterns despite differences in modeling approaches [8]. Their findings confirmed that China remained the dominant emitter in East Asia, contributing over 80% of total CO_2 emissions, followed by Japan and South Korea [8]. Through hotspot and driver analyses, the study identified persistently high-emission zones in Northern and Eastern China and emerging hotspots in the northwest. Economic activity and energy mix changes were found to be the primary drivers of emissions in high-impact areas, while regional characteristics influenced trends in lower-emission zones. The authors concluded with policy-relevant recommendations for spatially targeted carbon reduction strategies based on the observed patterns of emissions distribution and underlying drivers [8]. Employing a top-down spatial proxy model at a 1 km resolution, their study covered the period from 2012 to 2021 and integrated multiple datasets using geographically weighted regression techniques. This methodological approach aimed to enhance the spatial accuracy of sectoral emission estimates across diverse urban and industrial landscapes. To validate their inventory, the authors compared their results with established bottom-up datasets, including the Multi-resolution Emission Inventory for China (MEIC), and found a broad convergence in emission patterns despite differences in modeling approaches. Their findings confirmed that China remained the dominant emitter in East Asia, contributing over 80% of total CO_2 emissions, followed by Japan and South Korea. Through hotspot and driver analyses, the study identified persistently high-emission zones in Northern and Eastern China and emerging hotspots in the northwest. Economic activity and energy mix changes were found to be the primary drivers of emissions in high-impact areas, while regional characteristics influenced trends in lower-emission zones. The study concluded with policy-relevant recommendations for spatially targeted carbon reduction strategies based on the observed patterns of emissions distribution and underlying drivers [8].

The relationship between digital infrastructure and urban carbon emissions has become a prominent focus of contemporary environmental research. As cities across China invest in digital systems such as cloud platforms, data centers, smart grids, and communication networks, the resulting energy demands, and environmental consequences have sparked both concern and opportunity. Rather than presenting digital infrastructure as inherently beneficial or harmful, recent literature suggests that its environmental impact is highly contingent on local governance models, energy sources, technological maturity, and the extent to which these systems are embedded within urban planning frameworks.

A recurring theme across the reviewed literature is that digital infrastructure can reduce urban carbon emissions under certain conditions, especially when integrated with green energy systems and targeted policy frameworks. Studies focusing on Chinese urban centers consistently report improved emissions efficiency when digital transformation is paired with renewable energy adoption. For example, research shows that cities participating in the Broadband China initiative achieved reductions in total carbon emissions and carbon intensity [9,10]. These benefits were most pronounced in regions where digital infrastructure was deployed in tandem with investments in green technologies such as solar energy, smart grids, and energy-efficient cooling systems for data centers. The central mechanism at work here is energy substitution. As cities decouple digital expansion from fossil-fuel-based grids and shift toward clean electricity, the operational emissions of digital infrastructure decrease significantly.

However, not all studies identify the energy system as the dominant factor. A separate cluster of research highlights spatial planning and urban design as equally critical components in determining environmental outcomes. Studies by Song et al. (2024) and Mao et al. (2024) demonstrate that the environmental benefits of digital infrastructure are amplified when it is used to support compact, mixed-use urban development [11,12]. Digital systems such as real-time traffic monitoring, environmental sensors, and AI-enabled resource management platforms facilitate the optimization of transportation flows and the reduction of energy waste. In these contexts, the primary mechanism of emission reduction is structural rather than technological. By guiding the physical layout and operational flow of cities, digital tools indirectly minimize the need for high-emissions infrastructure such as private vehicles, inefficient public transport, and energy-hungry urban sprawl.

Although these findings reveal areas of convergence, they also uncover divergence regarding the most effective strategies. One important line of distinction is between studies that emphasize technological mechanisms versus those that focus on behavioral change. Ren et al. (2025) underscore the importance of digital literacy, public participation, and smart consumption tools in reducing household-level energy use [10]. For instance, smart meters, real-time consumption dashboards, and mobile applications that track carbon footprints have been shown to encourage behavioral shifts among citizens toward more sustainable practices. In contrast, Song (2024) argues that the bulk of emissions reductions observed in certain cities can be attributed to large-scale policy interventions, particularly those involving government-led investment programs and infrastructure coordination [11]. In these cases, the effect is top-down, with emissions reductions occurring not through individual behavior but through regulatory alignment, financial incentives, and administrative enforcement.

Another significant variable in the emissions outcomes of digital infrastructure is regional governance capacity.

Research conducted by Li and Tang (2024) and Deng and Zhong (2024) compares outcomes across cities in eastern, central, and western China [13,14]. While eastern cities benefited the most from digital infrastructure investments in terms of carbon efficiency, these results were not solely due to technological superiority. Instead, they were associated with more robust environmental governance systems, better fiscal resources, and stricter enforcement of emissions standards. By contrast, many Western cities with comparable digital systems failed to produce equivalent environmental benefits due to weaker regulatory institutions and inconsistent ESG reporting practices. This suggests that governance quality, and not merely infrastructure deployment, plays a central role in determining whether digital systems translate into real climate gains.

Another layer of complexity is added by studies that analyze temporal trends and infrastructure saturation. Korolev et al. (2023) found that the relationship between digital infrastructure development and urban carbon emissions follows a U-shaped curve [15]. In the early phases of development, emissions tend to rise due to the high energy input required for construction and network establishment. However, after a certain threshold is reached, emissions begin to decline as digital systems enable efficiencies in transportation, energy use, and industrial coordination. This inflection point appears to be linked with both technological maturity and policy adaptation. The implication is that cities must move beyond pilot projects and experimental technologies and toward full-scale integration in order to unlock the environmental benefits of digital infrastructure.

Another emerging insight concerns the interconnection between digital infrastructure and regional economic models. Cao and Wu (2025) argue that digital development does not merely influence emissions directly, but also reshapes industrial productivity, labor markets, and investment flows [16]. For example, their study shows that digital infrastructure enhances carbon productivity, defined as the economic output per unit of carbon emitted. This is particularly relevant in the construction and manufacturing sectors, where the adoption of digital tools for project management, logistics, and quality control leads to both economic and environmental improvements. However, the authors caution that these effects are unevenly distributed. Cities with strong pre-existing industrial bases and digital ecosystems tend to benefit disproportionately, while resource-constrained regions risk becoming locked into carbon-intensive development pathways.

Vora (2025) emphasizes this duality by arguing that digital infrastructure is increasingly indispensable to modern economic and administrative practice, but its environmental toll, largely driven by the energy requirements of data centers and computational hardware, cannot be overlooked [17]. The study highlights a set of technical and regulatory interventions that can mitigate these costs. These include improved hardware design, energy-efficient cooling systems, a shift to renewable energy sources, and smarter data processing protocols. However, the study also notes that these solutions are complex and expensive to implement, requiring alignment between public policy, private investment, and environmental standards. Vora ultimately calls for a reorientation of digital development policies to integrate environmental goals more explicitly, suggesting that policy-driven digital transformation can enhance both air quality and economic resilience [17].

Complementing this technological focus, other studies adopt a systemic, city-level perspective to assess the environmental impact of digital infrastructure deployment. A nationwide analysis covering Chinese cities between 2010 and 2021 constructed an index to measure the extent of digital infrastructure construction (DIC) and found a strong inverse correlation with urban carbon emissions [18]. In cities where DIC was more advanced, emissions intensity declined, even after controlling potential biases. These reductions were attributed not only to technological upgrades but also to broader societal factors such as increased public environmental awareness and green innovation adoption. Interestingly, the environmental benefits of DIC were more visible in western regions of China, where local governments adopted alternative mitigation strategies in the face of limited financial resources. These cities, having previously grappled with high emissions levels, implemented digital infrastructure with a clear environmental mandate, leading to relatively more impactful results [18].

This regional variation highlights that the success of digital infrastructure in reducing emissions is not uniform. While wealthier cities in eastern China had already begun integrating environmental standards into their infrastructure projects prior to the study period, cities in the west were more likely to adopt innovative approaches when supported by digital systems. This suggests that financial constraints do not necessarily preclude environmental progress if digital tools are used strategically.

Another study further deepens the analytical perspective by using statistical modeling and machine learning techniques to evaluate how digital infrastructure affects air quality and urban pollution across multiple cities [19].

This research provides quantitative confirmation that higher levels of digital infrastructure development are associated with measurable reductions in both carbon emissions and urban pollution indicators. The mechanisms include real-time emissions tracking, data-informed environmental planning, and predictive maintenance of infrastructure systems, all of which allow cities to respond more efficiently to environmental stressors [19].

In addition to the extensive body of Chinese research on digital infrastructure and emissions, comparable trends and challenges are observed in Europe and North America. Within the context of Europe, Wohlschlager et al. (2021) conducted a life cycle assessment to evaluate the direct environmental impacts of information and communication technology used in German smart grids, with a particular focus on intelligent metering infrastructure and decentralized flexibility markets [20]. Their analysis estimates that, by 2030, smart metering systems operating at the low-voltage level will contribute approximately 513,679 tons of CO_2-equivalent emissions annually. For households participating in decentralized flexibility markets, the associated digitalization measures are projected to generate 27 to 43 kg CO_2-equivalent per year. The study finds that most of this environmental burden stems from the production and operation of ICT hardware, rather than from data transmission itself. These findings highlight the critical importance of improving energy efficiency, extending the lifespan of digital components, and transitioning toward a low-carbon electricity supply to mitigate emissions. The authors also emphasize the need to evaluate emerging, more data-intensive applications in smart grids using similarly detailed environmental assessments. Furthermore, they suggest that future research should explore the indirect environmental impacts of digital technologies, particularly in relation to behavioral changes and the broader energy system, in order to inform more sustainable digital infrastructure designs within smart energy transitions [20].

In North America, Guidi et al. (2024) investigated the environmental implications of the rapid expansion of data centers in the United States, particularly in light of growing artificial intelligence adoption [21]. Analyzing 2,132 operational data centers from September 2023 to August 2024, the study quantified electricity usage, energy sources, and associated CO_2-equivalent emissions. The results revealed that U.S. data centers were responsible for over 4% of national electricity consumption during the study period, with 56% of this energy sourced from fossil fuels. This translated into more than 105 million tons of CO_2-equivalent emissions, approximately 2.18% of the country's total greenhouse gas emissions for 2023. Notably, the carbon intensity of data center operations surpassed the national average by 48%, underscoring the environmental cost of digital infrastructure expansion. The authors also introduced a scalable data pipeline and visualization framework that enables ongoing monitoring and assessment of the ecological footprint of data centers. Their findings highlight the urgent need for integrating decarbonization strategies, such as renewable energy sourcing and energy-efficient computing, into the design and operation of AI-driven digital infrastructure [21].

These cross-regional insights converge on three key points: first, the operational stage is the highest-emitting stage of digital infrastructure universally. Second, regional differences in energy systems, especially the share of renewables, create measurable variation in emissions intensity. Third, strong governance and regulation significantly enhance emission reductions, as evidenced by Europe's pact-based model alongside China's ESG-led, market-informed approach (**Table 1**). Meanwhile, the evolving pressures from AI workloads and water use highlight shared resource-stress concerns across all regions. Besides, by framing these international parallels, the manuscript can affirm that although the detailed case examples concentrate on China, the underlying lifecycle patterns and mitigation levers are also valid in Europe and North America. This comparative perspective enriches the review, providing analytical depth and greater credibility in presenting digitally enabled infrastructure as a global sustainability challenge.

Table 1. International Comparison of Digital Infrastructure Characteristics and Emissions Policies.

Region	Grid Carbon Intensity (gCO_2/kWh)	% Renewable Energy in Digital Sector	Average Data Center PUE	Mitigation Policies	ESG Enforcement Mechanisms
China	681	~30%	1.7	Broadband China, 5-Year ESG mandates	Mandatory ESG for tech zones
European Union	255	~40%	1.5	EU Digital Strategy, Green Deal	Carbon border adjustment & audits
United States	386	~28%	1.58	State-level incentives, DOE efficiency guidelines	Voluntary, sectoral reporting

Therefore, a system-oriented approach is essential. Policymakers and urban planners must recognize that digital infrastructure is not simply a technical fix, but a strategic platform whose impact will be shaped by how it is embedded into the physical, institutional, and behavioral fabric of the city. Investing in renewable energy alone is not sufficient unless paired with regulatory enforcement and public education. Similarly, data-driven decision-making is unlikely to succeed without interdepartmental coordination and long-term strategic planning. As cities worldwide continue to digitize in pursuit of sustainable development, the Chinese experience offers critical lessons about both the promise and the pitfalls of digital transformation (**Table 2**).

Table 2. Carbon Emissions Across the Lifecycle Stages of Digital Infrastructure.

Category	Lifecycle Stage	Primary Emission Source	Example Technologies	Emissions (kg CO_2e/unit)	Mitigation Potential	Best Practices	Supporting Technologies
Data Centers	Manufacturing	Semiconductor production, metal extraction	Servers, cooling systems	8–12	Medium	Sustainable sourcing	Green chips, life-cycle assessments
Data Centers	Operation	Electricity consumption (cooling, computing)	Power usage effectiveness (PUE)	4–6/server-year	High	PUE < 1.2, AI-assisted cooling	Liquid cooling, PUE tracking
Data Centers	Disposal	E-waste, landfill methane, informal recycling	Decommissioned servers, batteries	2–3/unit	Medium	Safe recycling channels	Circular economy platforms
Communication Networks	Manufacturing	Fiber optic production, antenna fabrication	5G towers, submarine cables	5–7	Medium	Eco-materials	Low-impact fiber tech
Communication Networks	Operation	Signal transmission energy, base station power draw	Mobile networks, satellite systems	3–4/network-day	Medium	Energy-efficient signal processing	Smart transmission scheduling
Communication Networks	Disposal	Non-biodegradable casing, PVC cables	Network routers, telecom hardware	1–2/unit	Low	Biodegradable casing	PVC alternatives
Artificial Intelligence	Training (Operation)	GPU/TPU energy for model training	Deep learning, generative models	20–50/model	High	Model pruning, quantization	Green AI, renewable data centers
Artificial Intelligence	Inference (Operation)	Frequent cloud or edge computing queries	Chatbots, vision systems	1–3/session	Medium	Efficient algorithms	Edge optimization
Artificial Intelligence	End-use Disposal	Device power draw, upgrade cycles	Edge devices, AI cameras	0.5–1/device	Low	Energy-aware device design	Low-power inference engines

Approaches to achieve a sustainable environment do not change the global outcome due to mostly impractical policies. Countries should manage how digital infrastructure is built and maintained. Digital infrastructure has raised various concerns in health and environmental organizations. Studies have shown that digital infrastructures support the development and economic goals. Research from China, for example, claims that the "Broadband China" strategy may achieve cleaner outcomes without decreasing productivity [9]. Using this policy as an experiment, researchers analyzed data from 2010 and 2019 to assess how digital infrastructure affects urban carbon emission efficiency. The findings show that digital expansion can improve total carbon emission performance at the city level, suggesting that digital systems can contribute to environmental goals if sustained in a studied way [9]. The reason it reduces the total carbon emissions is that data servers would have less pressure, which would lead to lower energy consumption to maintain data storage.

A study conducted by Song looks at how the "Smart City" policy influenced carbon emissions by focusing on cities between 2005 and 2020 in China [11]. The policy was treated as an experiment to examine how improving urban infrastructure with digital technologies would affect environmental outcomes. The results show that the digital development of infrastructure helped reduce carbon emission intensity in the cities that adopted the policy [11]. The impact extended to neighboring cities in China, showing a "spillover effect" where the emissions were not carried to other areas [11]. The effect was found within a 600 km range of where the policy was implemented, meaning that the environmental benefits of digital infrastructure emissions are not limited to specific areas [11]. The study highlights that smart infrastructure can lower emissions through planning, and the need to consider how these effects move across cities if the goal is long-term national change [11].

In the context of smart city development, advancing technological infrastructure alone is insufficient [22]. Public engagement and community promotion are equally essential to ensure that digital systems are accepted, effective, and aligned with sustainability goals [23]. Mak et al. (2021) explore the critical role of data openness in advancing scientific innovation, public engagement, and smart city development, focusing specifically on air quality information [24]. The study introduces a three-tiered Data Openness in Air Quality (DOAQ) framework, composed of 23 principles designed to assess effectively smart cities share, centralize, and make air quality data accessible. This framework quantifies openness using weighted formulas that prioritize different aspects of data availability and visibility. The DOAQ scores were applied to the world's top 50 smart cities and then compared with rankings from the Eden Strategy Institute and ONG&ONG Pte Ltd., alongside various social, political, and human development indicators. The results reveal moderate to strong correlations (ranging from 0.4 to 0.6), suggesting that air quality data openness serves as a reliable proxy for broader environmental data transparency in urban settings. The study also identifies best practices such as real-time air quality apps and forecasting tools, offering practical insights and criteria to guide cities in improving their environmental data strategies. Ultimately, the research provides a foundational model for evaluating and enhancing air quality data openness as a core component of smart city governance and public health awareness [24].

Mutambik et al. (2023) investigate the crucial role of public engagement in the successful implementation of smart city strategies, particularly within the context of Saudi Arabia's Vision 2030 [25]. While global efforts to transition toward smart urban systems are underway, the study highlights that such transformations cannot rely solely on government initiatives. Instead, active citizen participation is essential. The authors seek to identify the key external factors influencing individuals' intention to engage in smart city development and how these variables shape actual engagement behaviors. Using data collected from residents across ten Saudi cities involved in the national smart city plan, the study adopts a quantitative methodology supported by structural equation modeling (SEM). The proposed model tests the influence of five external variables: information availability, perceived benefits, social norms, behavior management, and social responsibility. Results reveal that information availability has a direct and significant impact on engagement behaviors, while the other variables indirectly contribute by shaping residents' attitudes toward participation. The study offers practical insights for policymakers, suggesting that enhancing public information channels and fostering a sense of social value and trust can promote deeper civic involvement. Despite its regional focus, the research provides a foundation for broader investigations into civic participation in smart city contexts globally [25].

The growth of digital infrastructure has the potential to reduce the effects of carbon emissions (**Figure 3**) [26]. Coordinated sustainable development efforts that include the study of the overall system can be the source of solutions to minimize risks. Analysis of data from 30 regions in China between 2013 and 2021 reveals an increase in digital economic activity alongside a significant reduction in carbon emissions by applying modern techniques like TOPSIS and PVAR models to control the growth of digital infrastructure [13]. The study demonstrates a relationship between digital economic growth and carbon emissions, suggesting that the expansion of the digital economy can align with environmental objectives if managed in a way that does not overwhelm the systems, creating more harm in power centers [13].

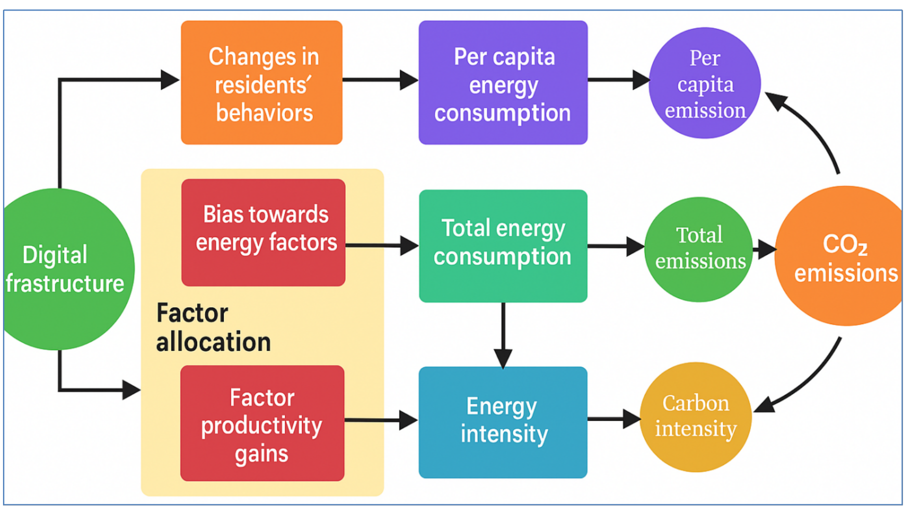

Figure 3. Causal Flow Diagram Illustrating the Impact of Digital Infrastructure on CO_2 Emissions. Source: the Authors, Adapted From [26].

After reviewing the process in which data storage works, the reliance on previous data storage models that are outdated can contribute to high levels of carbon emissions, air pollution, and inefficiency in maintaining the infrastructure will lead to worsening carbon levels and an acceleration in the pace of the climate [27]. Technology is regularly improved and updated, while the data storage is still running on outdated models that do not accommodate the improvements, leading to high carbon emissions. This approach is no longer sustainable, neither environmentally nor economically. A transition towards a low-carbon and waste-reducing development model that prioritizes efficiency and productivity has become essential [27]. Hence, digital development can be used as support to implement this method.

Data centers are among the largest contributors to carbon emissions within the digital infrastructure ecosystem. Their high energy demand stems not only from computational tasks and server uptime but also from extensive cooling requirements. As demand for cloud services and AI workloads increases, the environmental burden of data centers is expected to rise sharply, especially in regions still dependent on fossil-fuel-dominated energy grids.

However, targeted technological and energy solutions are emerging to mitigate these impacts. Renewable energy integration, such as solar-powered data centers and wind-powered edge nodes, has been piloted in North America and parts of Europe, showing measurable reductions in operational emissions. Companies like Google and Microsoft have committed to hourly carbon-free energy models for data center operations by 2030, establishing a path for replication in emerging markets [28].

In addition, recent breakthroughs in nanomaterial science present an innovative approach to several environmental issues [29–31]. For example, nanofluid-based heat exchangers and phase-change materials engineered at the nanoscale allow for more efficient heat transfer compared to traditional Heating, Ventilation and Air Conditioning (HVAC) systems [32]. These materials enable lower energy consumption for cooling without sacrificing computational performance, offering scalable applications for high-density data centers in urban environments. Furthermore, using sustainable and natural insulation materials plays a great role in reducing urban energy needs for cooling purposes [33].

Integrating such energy-efficiency solutions directly into the data center lifecycle, especially during the design and retrofitting phases, can significantly reduce emissions. Doing so not only aligns with national decarbonization goals but also helps shift digital infrastructure toward long-term environmental sustainability.

Urban spatial configurations have a profound influence on carbon emissions [34]. Dispersed, low-density developments often correlate with increased energy use in transportation and infrastructure maintenance, while compact urban forms tend to facilitate more sustainable mobility and building practices. However, rapidly expanding digital infrastructure in cities—including the deployment of 5G towers and data node clusters, risks intensifying emissions unless spatial planning is coupled with environmental foresight [35].

Emerging mitigation strategies emphasize the integration of green infrastructure into urban digital systems. Research demonstrates that strategically located urban green spaces, such as green roofs, tree-lined boulevards, and ecological corridors, not only absorb carbon dioxide but also regulate land surface temperatures affected by digital infrastructure heat output [36]. Furthermore, embedding solar panels into smart street furniture, transit shelters, and even data center rooftops presents a dual-use opportunity for emissions control. These adaptations are especially effective in cities struggling with land constraints, offering space-efficient interventions that co-exist with expanding digital networks.

4. Role of Artificial Intelligence in Carbon Emissions and Sustainability

This study claims that the development of digital infrastructure has the potential to make situations better instead of escalating them. One example is the use of Digital Twins, which reflects the event of the real world object using sensors and data streams, while connecting them with intelligent computing, which has made the infrastructure more stable during the process of reducing its environmental impact [37]. The tools implemented have the ability to influence the global outcome of carbon emissions. Lowering energy use in buildings and reducing transport emissions also improves power systems [37]. The data shows that energy use in buildings dropped by 25%–30% using this strategy [37]. Designing the predicting and adjusting systems controls the management of how the power systems work, which makes them adjust to the point of reaching climate targets. They also provide clear planning and policy-making strategies, specifically in cities that are developing or have unstable climate conditions. As more cities adopt Digital Twins tools, future research is expected to update how they can be applied more to support long-term environmental goals [37].

AI operated by digital infrastructure is still in a stage where there are possibilities for innovation and discovery, but the environmental impact of powering the digital system to generate AI is very high. The evidence in "Carbon Footprint of Artificial Intelligence in Materials Science" shows that the carbon footprint associated with AI in digital infrastructure has severe concentration and is still expected to increase due to its reliance on it in modern technology systems [15]. Concerns are raised towards AI being part of modern society's practices, considering the emissions it generates. The study argues that fully understanding these impacts is a necessary step toward building a cleaner and more responsible approach to AI building and scientific research [15]. Lack of awareness regarding digital infrastructure risks contributes to the very problematic environmental issues that are in need to be solved. For this reason, Korolev emphasizes the need for more approaches to monitor and reduce greenhouse carbon emissions within the field of AI [15].

In contrast, another claims that AI is often criticized for its energy consumption without considering its benefits. The data used by Wang et al. (2024) highlights that its impact has the ability to support environmental goals. The authors states that AI contributes to the reduction of environmental emissions and carbon footprints, also helping accelerate the shift towards cleaner energy systems [38]. As the data shows, for every 1% rise in AI development, several outcomes happen: energy consumption rises by 0.0025%, environmental emissions drop by 0.0018% and carbon footprint is reduced by 0.0013% [38]. Results show that AI is effective at its peak, the more it consumes power and energy from digital servers, also considering its ability to decrease climate pollution and reduce environmental concerns [38].

The issue of underestimating the environmental impact of machine learning models becomes evident when examining the inconsistencies in how carbon emissions from the models are reported. Luccioni et al. (2022) developed an approach that focuses on the energy production efficiency of data centers, labeling them as Power Usage Effectiveness (PUE) [39]. The study also presents a comparison between carbon emissions calculated with and without PUE included [39]. The result values for the data centers, including the PUE, are between 1.08 and 1.2; their overall contribution to emissions is minimal in comparison to the results without PUE, which are still high [39]. However, the authors point out that this situation narrows the focus and captures only a specific part of the total environmental impact. It excludes highly important sources such as emissions associated with digital infrastructure production, as well as the energy consumed throughout the maintenance and implementation stages of the infrastructure [39]. Additionally, the study also goes further by estimating the carbon footprint of the intermediate experimentation and evaluation stages conducted during the Big Science workshop, which is a global experiment aiming to create an open AI model, highlighting that the emissions extended beyond the experiment [39].

Another study by Lannelongue et al. (2021) reported a foundation for developing green computing systems within different technological servers [40]. The authors discuss the impact of carbon emitted from high pressures on digital infrastructure and cloud computing, encouraging practical solutions to address it [40]. Recognizing and addressing these emissions is a necessary first step toward ensuring that progress in materials science is not made at the expense of environmental sustainability. An analysis of the energy consumption and carbon emissions related to different generative AI (GAI) models offers projections of their carbon footprint. The findings of a study by Ding et al. (2024) highlight that GAI requires efficient energy production, making it a contributor to carbon emissions [41].

5. Social Media and Digital Behavior's Carbon Impact

Kusundal et al. (2023) show, based on data, that substantial carbon dioxide emissions are released by certain parts of the "green" internet, which means making the internet cleaner by reducing its carbon footprint and energy consumption (**Figure 4**). Despite the interpretation, the numbers collected reflect the emissions of a single day of human activity and practices [42]. Regardless of the amount of individual emissions themselves, which are imbalanced, the total is still greatly responsible for causing global concern [42]. It is difficult to completely prevent these emissions from spreading in the air, though some mitigations can reduce the long-term impacts on health. Furthermore, the authors discuss that the data collected highlight the overuse of emails and how they lead to an increase in the digital carbon footprint [42]. The internet has many different tasks that make it a necessity; emails are considered the primary mediator of long-distance communication. From a certain perspective, this situation is viewed as a benefit of modern technology, not considering that it also adds to carbon emissions and increases the risk of global warming. Small changes in how data servers are used can highly impact the outcome of global emissions, for example Qatar's usage of carbon capture and storage systems in gas and industrial facilities, operating them to capture carbon before it is released in the air can restore climate stability, as well as machinery that can convert carbon emissions into less harmful compounds.

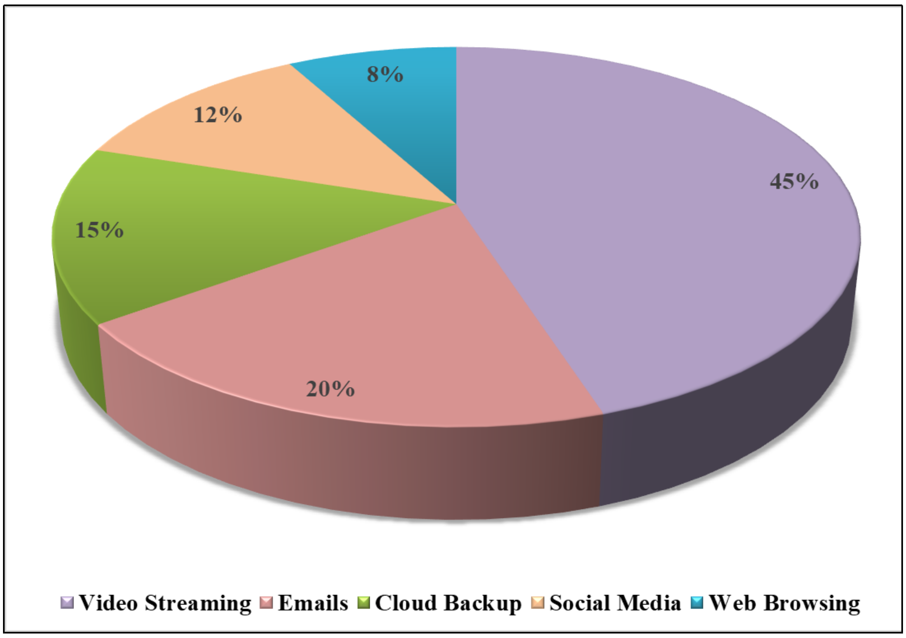

Figure 4. Estimated Daily Contribution of Common Digital Activities to the Carbon Footprint. Streaming Accounts for the Largest Share of Emissions, Followed by Emails and Cloud Backups, Adapted From [42].

Information and communication technology's (ICT) influence is growing deeper across different aspects of modern technology [43]. Every digital action that creates data must be powered and stored, then transferred by energy-consuming infrastructure [43]. The digital activities continue to add to the global carbon footprint [43]. In social media, scrolling and streaming, or posting, contribute to environmental pollution. A study by Naeem et al. (2023) focused on quantifying the emissions produced by social media platforms. The study states that one hour of online video streaming generates 280.26 grams of CO_2, and the Andrae method calculates only 72 grams [44]. Highlighting the inconsistencies in carbon accounting approaches, suggesting that it is difficult to accurately measure the amount of emissions that could be more intense than calculated.

Furthermore, this study explored the level of awareness among social media users in Punjab, Pakistan, regarding their digital carbon footprint and whether individual behavior influences efforts to reduce it [44]. To achieve this, the researchers applied statistical analysis to examine the relationships between variables. The findings indicate that participants came from different backgrounds and showed varying levels of engagement in digital practices [44]. The practices included monitoring screen time, applying energy-saving settings on smartphones, and reducing the number of photos and videos shared on social media platforms [44]. The results suggest that digital behaviors can reflect the awareness and willingness to adapt small changes aiming to minimize one's digital carbon footprint [44].

6. Environmental Impacts of Digitalization

According to Li et al. (2025), the total carbon emissions from the generation of power and electricity transmission systems were compared with existing research and official data from the Ministry of Ecology and Environment to check their reliability [45]. The findings suggest that the carbon emissions of power generation are within the expected range in previous studies with similar calculations. Moreover, the difference with the Ministry's data was under 10%, indicating that the results are considered reliable to be used in calculating the carbon footprint of the power system [45]. However, there was a noticeable difference between the results of the author's study regarding carbon emission for energy production systems and the numbers reported by the Ministry [45]. This gap may be due to outdated information or missing details in earlier calculations. Since it is difficult to access recent data containing details on China's power transmission systems, the study relies on the Ministry's published figures to calculate the overall carbon footprint [45]. Keeping updated data on carbon infrastructure emissions is difficult, which causes the study to assume that these results remain steady across time and different regions [45].

Green communications refer to the implementation of energy-storing technologies in communication and networking systems [46]. The study analyzes the carbon footprint associated with computing facilities and internet usage within an educational institution [46]. The findings reveal that emissions are generated through the institution's computing infrastructure, due to its tasks that support educational activities [46]. In Australia, the findings estimate that each internet subscriber contributes approximately 81 kg of carbon emissions [47]. The preparation and operation of voting software can also be a reason to generate carbon dioxide emissions.

The internet is known to have several effects on carbon footprint output, and it still forms a part of communication methods today. It supports people to stay connected and gives students access to important educational information [48]. The impact of the digital infrastructure on carbon emissions reveals geographical imbalances [49]. The digital age has redefined how people connect, learn, and share, yet its environmental footprint—particularly the carbon emissions from digital infrastructure—varies significantly across regions. A recent peer-reviewed study in Nature Communications finds that average global users generate approximately 229 kg CO_2-eq per year through web surfing, streaming, and online communication—accounting for about 3–4% of annual per capita greenhouse gas emissions. Crucially, this number fluctuates based on regional electricity mix: just 146 kg CO_2-eq in hydro-powered Norway, versus 327 kg CO_2-eq in fossil-dependent India. This highlights how infrastructure and power sources drive geographical imbalances in digital carbon footprints [50].

Beyond access and use, the internet's supporting systems themselves contribute to emissions unevenly. A study by Batmunkh (2022) examined major streaming platforms such as Netflix, TikTok, Facebook, and YouTube, and concluded that energy-intensive services like HD video dramatically increase carbon output, illustrating that not all online activities carry equal environmental cost [51].

Geographic disparities are also evident in the global impacts of digital infrastructure development. A recent study by Liu et al. (2025) reported that although the digital economy aids carbon emission reduction through technological efficiencies, the benefits are not evenly experienced. Regions with advanced digital systems and energy-efficient networks reap more gains, while areas with outdated or power-intensive infrastructure remain carbon-intensive recipients of digital growth [52].

7. Conclusions

7.1. General Findings

This review examined the environmental costs of digital infrastructure across its full lifecycle, including construction, operation, maintenance, and end-of-life phases. Drawing on 52 peer-reviewed studies published between 2010 and 2025, the analysis covered a wide range of digital systems including data centers, cloud platforms, artificial intelligence, and digital behavior patterns. While digital infrastructure is often celebrated for enabling sustainability through optimization and efficiency, this review finds that it also contributes significantly to global greenhouse gas emissions. These emissions stem not only from operational energy use but also from the construction of networks, the manufacturing of hardware, and the energy-intensive training of machine learning models.

Urban-scale studies, particularly those based in China, show that digital development can align with climate mitigation objectives when paired with renewable energy integration and strict environmental regulation. Initiatives such as Smart Cities and Broadband China demonstrate that emissions reduction is possible when digital infrastructure is supported by green governance. Another key finding is the role of digital behavior, including streaming, cloud storage, and email usage, which cumulatively add to the carbon footprint but are frequently excluded from infrastructure-level assessments. In parallel, promising mitigation strategies such as the use of nanotechnology for air purification, the adoption of artificial intelligence for system optimization, and the integration of urban green spaces have begun to emerge. Together, these findings support a systems-level understanding of how digital infrastructure can both exacerbate and help solve environmental challenges, depending on how it is designed, used, and regulated.

7.2. Limitations

Several limitations must be acknowledged. First, the scope of the review was limited to studies published between 2010 and 2025 and written in English. This may have excluded earlier foundational work and valuable insights from non-English academic communities. Second, although the review is based on a lifecycle perspective, many of the cited studies do not provide complete or precise data for upstream and downstream emissions. Gaps remain in full account for emissions from hardware manufacturing, network expansion, and electronic waste disposal.

Geographically, the review reflects a strong focus on China due to the density and quality of published research on digital infrastructure in that context. As such, its findings may not be universally applicable to regions with different energy mixes, digital development trajectories, or regulatory capacities. Furthermore, while the paper mentions broader sustainability elements such as ESG and social behavior, it does not offer an in-depth analysis of social or economic dimensions, which may limit its application in interdisciplinary policymaking. Lastly, some of the emerging solutions discussed, such as nanotechnology and artificial intelligence for emissions control, are still in developmental phases and lack long-term empirical validation.

7.3. Future Research Outlook

Future research should focus on conducting comprehensive lifecycle assessments of digital infrastructure that include hidden emissions from hardware production, equipment transportation, system upgrades, and end-of-use disposal. More consistent and standardized carbon accounting methodologies are needed to better capture the true environmental impact of data centers, machine learning systems, and network-intensive technologies. Researchers should also explore the cumulative effect of digital user behavior and identify behavioral interventions, such as energy-efficient interface design or digital detox strategies, that could reduce emissions without compromising access or functionality.

There is a growing need for empirical evaluations of emerging solutions, particularly in the application of nanomaterials for air purification in server rooms, the integration of decentralized renewable energy sources in data operations, and the use of artificial intelligence for infrastructure control. Comparative studies across countries would help to identify success factors in governance, financing, and institutional design that promote environmentally sustainable digital transformation. In addition, future work should investigate how digital infrastructure interacts with trade, supply chains, and labor practices, especially in the context of low- and middle-income countries.

To address these complex questions, interdisciplinary collaboration will be essential. Experts in environmental science, engineering, urban studies, data ethics, and economics must work together to develop integrated models and policies. Policymakers, in turn, must consider digital infrastructure not just as a tool for economic growth but as a significant driver of environmental change. By taking a more integrated and proactive approach, future research can help ensure that digital infrastructure becomes a force for climate resilience and sustainable development rather than a growing contributor to environmental degradation.

Author Contributions

Conceptualization, A.A. and R.I.; methodology, A.A.; validation, R.I.; formal analysis, A.A.; investigation, A.A.; resources, A.A.; data curation, A.A.; writing—original draft preparation, A.A.; writing—review and editing, R.I.; supervision, R.I.; project administration, R.I. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No data was curated for this review paper.

Acknowledgments

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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