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Invisible Pollutants Revisited: A Review of Emerging Environmental Risks from Digitalization and Data Infrastructure

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ABSTRACT

The rapid digitalization of society has ushered in an era of unprecedented connectivity and data-driven innovation, yet it has also introduced a suite of "invisible pollutants" – environmental externalities that are often overlooked in discussions of sustainability. This narrative review reexamines these risks, conceptualizing data centers, digital waste streams, and escalating energy demands as novel forms of pollution that contribute to climate change, resource depletion, and ecological degradation. Drawing on peer-reviewed literature from 2019 to 2025, we synthesize evidence on the environmental footprints of digital infrastructure, including greenhouse gas emissions from energy-intensive operations, water consumption for cooling, electronic waste generation from hardware lifecycles, and supply chain impacts from rare earth mineral extraction. Key themes include the exponential growth of data centers driven by artificial intelligence and cloud computing, which exacerbate energy demands and carbon emissions, and the mismanagement of digital waste, leading to toxic pollution and health hazards. The review highlights mitigation strategies such as energy-efficient designs, circular economy approaches, and regulatory frameworks, while underscoring the novelty of treating these digital elements as pollutants to foster interdisciplinary discourse. Objectives are to provide a comprehensive overview of emerging risks, identify knowledge gaps, and propose pathways for sustainable digitalization. Ultimately, this work advocates for integrating environmental considerations into digital policy to align technological progress with planetary boundaries.

Keywords: *Digital pollution, Data centers, Energy consumption, Electronic waste, Environmental sustainability, Artificial intelligence*

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INTRODUCTION

The digital revolution has transformed virtually every aspect of modern life, from communication and commerce to healthcare and education. With global internet penetration exceeding 60% and average daily online time surpassing seven hours per person, digital technologies have become integral to societal functioning (Istrate *et al*., 2024). However, this proliferation has come at a significant environmental cost, often manifesting in subtle, "invisible" ways that evade traditional pollution paradigms. Historically, environmental risks have been associated with tangible emissions like industrial smoke or chemical runoff. In contrast, the externalities of digitalization – such as the energy voracity of data centers, the accumulation of digital waste, and the indirect resource demands of data infrastructure – represent a new category of pollutants that are diffuse, global in scale, and intertwined with technological progress.

This review revisits these invisible pollutants, building on earlier conceptualizations while emphasizing their emergence in the context of accelerating digitalization. Data centers, for instance, serve as the backbone of cloud computing and artificial intelligence (AI), yet their operations consume vast amounts of electricity, contributing to greenhouse gas (GHG) emissions comparable to entire industries (Graefen *et al*., 2023; Virmani, 2025). Similarly, digital waste encompasses not only physical electronic waste (e-waste) from discarded devices but also the intangible waste of obsolete data and inefficient algorithms, which perpetuate energy demands without commensurate value. Energy demand itself acts as a pollutant by straining power grids, promoting fossil fuel reliance, and exacerbating climate change (Dhanasekar *et al*., 2022; de Vries-Gao, 2025).

The background for this review is rooted in the dual-edged nature of digital technologies. On one hand, they enable sustainability advancements, such as optimized energy grids and precision agriculture (Efremov, 2023; Li *et al*., 2025). On the other, unchecked expansion amplifies environmental pressures, with global data center energy use projected to rise significantly by 2030 (Mytton, 2021; Nguyen & Hoang, 2022). Recent events, including the COVID-19 pandemic and the AI boom, have intensified these trends, with remote work and machine learning models driving exponential data growth (Trung *et al*., 2022; Virmani, 2025). Peer-reviewed studies from 2019 to 2025 reveal a consensus on these risks, yet gaps persist in holistic assessments that treat digital elements as pollutants.

The objectives of this review are threefold: (1) to provide a thematic synthesis of the environmental risks posed by digitalization and data infrastructure, framing them as invisible pollutants; (2) to evaluate mitigation strategies and their efficacy based on current literature; and (3) to identify research gaps and future directions for achieving sustainable digital ecosystems. By adopting a narrative approach, this article organizes evidence thematically, avoiding empirical methods or original data, and focuses on interdisciplinary insights from environmental science, technology studies, and policy analysis. Ultimately, this work aims to bridge the divide between digital innovation and environmental stewardship, urging a reevaluation of how we quantify and address the hidden costs of our data-driven world.

The expansion of digital infrastructure and data centers

The rapid expansion of digital infrastructure, particularly data centers, has become a defining feature of contemporary digitalization. Data centers form the physical backbone of cloud computing, artificial intelligence, and global data exchange by hosting servers, storage systems, and networking equipment essential for continuous data processing. Their growth has accelerated exponentially in response to the proliferation of internet-connected devices, high-definition streaming platforms, social media ecosystems, and data-intensive AI applications. By 2024, global data center capacity had expanded substantially, with the United States alone hosting thousands of facilities that collectively consume more than 4% of national electricity production (Ncube *et al*., 2023; Virmani, 2025). This expansion represents not only a technological transformation but also a significant environmental phenomenon, as data centers embody "invisible pollutants" through their intensive use of energy, water, and material resources.

Recent literature emphasizes the unprecedented scale and trajectory of this growth. Projections suggest that global data center energy demand could account for between 8% and 21% of total electricity consumption by 2030, depending on technological efficiency and policy intervention scenarios (Mytton, 2021; FigueroaValverde *et al*., 2023). This surge is driven by multiple converging trends, including the Internet of Things (IoT), fifth-generation (5G) communication networks, and the widespread deployment of AI models, all of which require hyperscale facilities capable of processing and storing zettabytes of data (Okoro *et al*., 2023; Virmani, 2025). Similar patterns are observed in China, where large-scale investments in broadband infrastructure and computing capacity have enhanced economic productivity and industrial efficiency, while simultaneously placing increasing pressure on national energy systems (Fitero *et al*., 2023; de Vries-Gao, 2025).

Table 1. Global Data Center Energy Consumption and Projections

Region/Country	Current Energy Use (% of total electricity)	Projected 2030 Energy Demand (% of total electricity)	PUE Range	Water Usage (million m^3/year)
USA	4%	8–21%	1.2–1.8	731–1,125
China	3%	10–18%	1.3–1.7	N/A
Global Average	2–3%	5–15%	1.3–1.5	N/A

Thematically, the literature conceptualizes data center expansion as a form of indirect environmental pollution rooted in continuous and escalating energy demand. Unlike traditional industrial facilities, data centers operate uninterrupted, requiring constant power and cooling to maintain operational stability. Power usage effectiveness (PUE) metrics reveal persistent inefficiencies, particularly in legacy facilities, where PUE values often exceed 1.5 (Mytton, 2021). Such inefficiencies imply that for every unit of energy consumed by computing processes, additional energy is expended on cooling, power conversion, and auxiliary systems, thereby intensifying indirect greenhouse gas emissions (Virmani, 2025). Furthermore, the geographic distribution of data centers critically shapes their environmental footprint. Facilities located in water-stressed regions exacerbate local resource scarcity, while those dependent on fossil fuel–dominated electricity grids contribute disproportionately to carbon emissions (Rutten *et al*., 2022; Virmani, 2025).

Social and regional dimensions further complicate these environmental impacts. In the United States, data center clustering in specific regions creates localized environmental burdens. Midwestern states offer opportunities for renewable energy integration but face limitations in grid infrastructure, whereas coastal regions rely more heavily on hydropower, which entails higher water consumption and ecosystem disruption (Siddiqi *et al*., 2022; Virmani, 2025). Collectively, the literature positions data center expansion as a central node within the broader digital pollution nexus, emphasizing the need for spatially optimized planning, infrastructure modernization, and policy coordination to mitigate associated environmental risks (Mytton, 2021; Xie *et al*., 2023; Virmani, 2025).

Energy consumption and carbon emissions

Energy consumption represents one of the most significant invisible pollutants associated with digital infrastructure. Data centers, communication networks, and end-user devices collectively drive substantial greenhouse gas emissions, transforming digital activity into a major contributor to climate change. Recent assessments estimate that global digital content consumption alone generates approximately 229 kg CO_2-equivalent per user annually, accounting for up to 40% of the per capita carbon budget required to limit global warming to 1.5°C (Hultström *et al*., 2023; Istrate *et al*., 2024). These emissions arise from a combination of operational electricity use, embodied emissions from hardware manufacturing, and energy losses during data transmission, rendering energy demand a pervasive environmental externality.

Empirical studies quantify the scale of these impacts at both national and global levels. In the United States, AI-focused servers are projected to emit between 24 and 44 million tons of CO_2-equivalent annually by 2030, with operational energy consumption representing the dominant contributor relative to infrastructure construction (Cissé *et al*., 2024; Virmani, 2025). Globally, the information and communication technology (ICT) sector accounts for approximately 2–3% of total electricity use and emits an estimated 1.0–1.7 Gt CO_2-equivalent per year, corresponding to 1.8–2.8% of total anthropogenic greenhouse gas emissions (Istrate *et al*., 2024). Within data centers, cooling systems consume 38–43% of total energy, while servers account for 43–52%, underscoring persistent efficiency challenges (Mytton, 2021). Regional disparities further exacerbate emissions intensity; electricity grids heavily reliant on fossil fuels, such as those in India, generate significantly higher per capita emissions (327 kg CO_2-eq/user/year) compared to hydropower-dominated systems such as Norway's (146 kg CO_2-eq/user/year) (Istrate *et al*., 2024).

Thematically, the literature explores multiple mitigation pathways to address these emissions. Improvements in PUE, adoption of innovative cooling strategies such as free cooling (which can reduce energy use by 30–40%), and large-scale integration of renewable energy sources are widely proposed (Mytton, 2021). Evidence from China suggests that digital infrastructure development can enhance energy–environmental efficiency through technological upgrading and industrial restructuring, particularly in eastern regions where emissions reductions have been observed (de Vries-Gao, 2025). However, rebound effects remain a critical concern, as efficiency gains often lead to increased digital consumption, partially offsetting environmental benefits (Istrate *et al*., 2024).

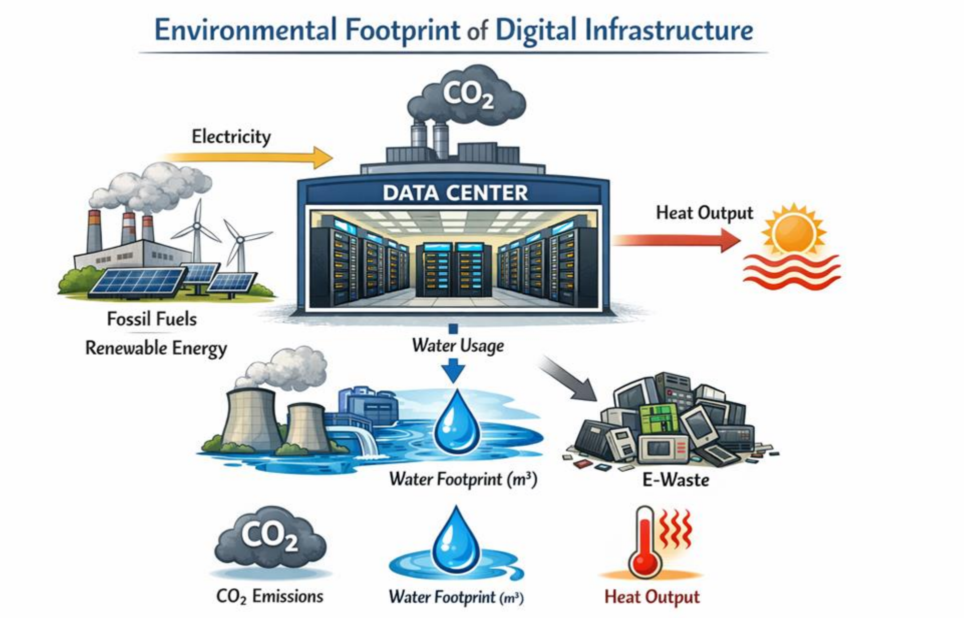

Figure 1. Environmental Footprint of Digital Infrastructure

The rapid expansion of AI and cloud computing further amplifies these risks. Training large-scale AI models can consume energy equivalent to that used by an average household over an entire year, significantly increasing carbon intensity (Virmani, 2025). Proposed net-zero pathways include aggressive grid decarbonization, which could reduce emissions by approximately 15%, and extending device lifespans, potentially decreasing mineral and energy demand by 29–32% (Istrate *et al*., 2024; Virmani, 2025). Nonetheless, uncertainty surrounding future growth trajectories suggests that, without targeted interventions, digital energy consumption may undermine global climate mitigation goals, reinforcing its characterization as a novel and largely unregulated pollutant (de Vries-Gao, 2025; Virmani, 2025).

Water usage and resource depletion

Water consumption constitutes another critical but often overlooked invisible pollutant associated with digital infrastructure, particularly through data center cooling systems that rely on large-scale water evaporation to dissipate heat. Projections indicate that AI-driven servers in the United States alone could generate annual water footprints ranging from 731 to 1,125 million cubic meters by 2030, with indirect water use linked to electricity generation accounting for approximately 71% of total consumption (Virmani, 2025). This level of demand places significant strain on water resources, especially in arid and semi-arid regions where data centers compete directly with agricultural, industrial, and domestic water users.

The literature provides detailed assessments of these impacts. Cooling systems dominate direct water consumption, representing nearly 29% of total water footprints, while efficiency indicators such as water usage effectiveness (WUE) reveal substantial variation and inefficiency across facilities (Virmani, 2025). Global estimates associate AI systems with 32.6–79.7 million tons of CO_2 emissions alongside extensive water demands, particularly in regions reliant on water-intensive hydropower generation (Virmani, 2025). In water-stressed environments, these pressures contribute to habitat degradation, ecosystem disruption, and heightened scarcity risks, positioning water use as a hidden but critical cost of digitalization (Mytton, 2021).

Thematically, studies propose several mitigation strategies to address water-related impacts. Advanced liquid cooling technologies, improved utilization rates, and operational optimization can reduce water footprints by approximately 1.6–5.5% (Virmani, 2025). Strategic siting of data centers in regions with low water scarcity, such as parts of the US Midwest, has the potential to reduce water consumption by up to 52% (Virmani, 2025). Decarbonization of electricity grids offers additional co-benefits, enabling reductions of up to 2.5% in water impacts through decreased reliance on water-intensive power generation (Virmani, 2025). Conversely, worst-case scenarios characterized by inefficient cooling and rapid demand growth could increase water footprints by up to 2%, highlighting the necessity of regulatory oversight and enforceable sustainability standards (Mytton, 2021).

Resource depletion extends beyond water to encompass mineral extraction, as digital hardware requires substantial quantities of rare earth elements and metals. End-user devices alone account for approximately 55% of per capita mineral capacity use, driven largely by gold extraction for electronic circuits (Istrate *et al*., 2024). These material demands exacerbate upstream environmental degradation and supply chain vulnerabilities, reinforcing the characterization of digital infrastructure as a multidimensional pollutant with far-reaching ecological consequences (Oo *et al*., 2023).

Digital and electronic waste

Digital and electronic waste constitutes one of the fastest-growing pollution streams globally, encompassing both tangible electronic waste (e-waste) from discarded hardware and intangible digital waste arising from data redundancies, inefficient storage, and obsolete digital processes. Although digital waste is often perceived as immaterial, it produces substantial environmental burdens through energy consumption, toxic material release, and ecosystem contamination. Global e-waste generation reached approximately 53.6 million metric tons in 2019 and is projected to increase to nearly 74 million metric tons by 2030, yet only 17–20% of this waste is formally recycled (Jain *et al*., 2023; Aslan *et al*., 2024; Xiao *et al*., 2025). The remaining majority is improperly managed, leading to the release of hazardous substances such as heavy metals, brominated flame retardants, and dioxins, which contaminate air, soil, and water systems (Manganelli *et al*., 2021; Xiao *et al*., 2025).

The literature identifies multiple sources and pathways of digital and electronic waste accumulation. The information and communication technology (ICT) sector is a major contributor due to rapid technological obsolescence and short device lifespans, often ranging from 6 to 12 months for consumer electronics (Manganelli *et al*., 2021; Xiao *et al*., 2025). Both households and commercial entities contribute significantly, accounting for an estimated 15–79% of total e-waste generation depending on regional consumption patterns (Manganelli *et al*., 2021; Xiao *et al*., 2025). In developing economies, the challenge is particularly severe. India, currently the third-largest producer of e-waste worldwide, relies heavily on informal recycling systems that process nearly 90% of discarded electronics (Xiao *et al*., 2025). These informal practices expose workers to toxic fumes and residues, resulting in elevated risks of respiratory diseases, neurological disorders, and various cancers (Xiao *et al*., 2025).

Beyond localized pollution, digital waste also contributes to climate change. Incineration and landfilling of electronic waste generate greenhouse gases (GHGs), including methane and hydrochlorofluorocarbons (HCFCs), which intensify global warming (Jain *et al*., 2023). The environmental consequences of improper disposal are well documented. Open burning releases dioxins and furans into the atmosphere, compounds strongly associated with carcinogenic and endocrine-disrupting effects (Aslan *et al*., 2024; Xiao *et al*., 2025). Soil contamination occurs through the leaching of heavy metals such as lead, cadmium, and arsenic, which degrade soil fertility and disrupt microbial ecosystems (Aslan *et al*., 2024; Xiao *et al*., 2025). Water systems are similarly affected, particularly by mercury and persistent organic pollutants, resulting in bioaccumulation and long-term ecological damage (Aslan *et al*., 2024; Xiao *et al*., 2025).

Human health impacts are a central concern in the literature. Chronic exposure to lead and mercury has been linked to neurological impairment, developmental disorders, and cardiovascular diseases (Jain *et al*., 2023; Xiao *et al*., 2025). Informal recycling workers, including women and children, exhibit significantly higher concentrations of dioxins and toxic metals in biological samples, underscoring severe occupational health inequalities (Jain *et al*., 2023; Xiao *et al*., 2025).

Mitigation strategies increasingly emphasize circular economy frameworks as a pathway to reduce the environmental footprint of digital waste. Reuse and refurbishment of electronic devices can save up to 60% of the energy required for manufacturing new products, while recycling through urban mining enables the recovery of approximately 61% of valuable metals contained in discarded electronics (Aslan *et al*., 2024). Advances in eco-design, including modular architectures and biodegradable or recyclable materials, further support waste reduction at the source (Aslan *et al*., 2024). Policy instruments such as extended producer responsibility (EPR) schemes and international agreements like the Basel Convention aim to regulate hazardous waste flows and curb illegal e-waste trade; however, significant implementation gaps and enforcement challenges remain, particularly in low- and middle-income countries (Jain *et al*., 2023; Aslan *et al*., 2024). Recognizing digital waste as a persistent pollutant highlights the urgent need for formalized recycling systems, technological innovation, and coordinated global governance (Manganelli *et al*., 2021).

Supply chain and material impacts

The environmental footprint of digital technologies extends far upstream into supply chains, where resource extraction and manufacturing processes generate largely invisible yet significant pollutants. The production of digital infrastructure relies heavily on rare earth elements (REEs), which are essential for servers, semiconductors, data centers, and consumer devices. Mining and processing of REEs are resource-intensive activities associated with land degradation, water pollution, and toxic waste generation. China's dominance in the production of heavy REEs, particularly terbium, has created structural vulnerabilities in global supply chains. Due to stricter environmental regulations, Chinese production of heavy REEs declined by nearly 90% between 2007 and 2018, resulting in supply shortages and market instability (Oo *et al*., 2023).

Existing literature highlights critical bottlenecks in REE supply. Terbium shortages in China alone reached approximately 3,300 tons following mine closures, as many facilities failed to meet updated environmental standards due to outdated extraction technologies (Oo *et al*., 2023). On a global scale, mining activities contribute an estimated 1.4–5.9% of total greenhouse gas emissions and are frequently associated with social challenges, including unsafe labor conditions and child labor practices (Aslan *et al*., 2024). Notably, digital consumption accounts for nearly 55% of per capita mineral capacity use, with embodied environmental impacts in electronic devices representing between 32% and 92% of their total lifecycle emissions (Istrate *et al*., 2024).

Thematically, supply chains amplify environmental risks through deforestation, acid mine drainage, soil erosion, and emissions generated during extraction and processing stages

(Oo *et al*., 2023; Aslan *et al*., 2024). Projections indicate that terbium shortages could increase by a factor of 2–5 by 2060, driven by accelerating demand from electric vehicles, renewable energy technologies such as wind turbines, and expanding digital infrastructure (Oo *et al*., 2023). Proposed mitigation strategies include the adoption of green mining techniques, such as electrokinetic extraction processes, increased recycling rates capable of alleviating 24–36% of future shortages, and diversification of supply through imports and secondary sourcing (Oo *et al*., 2023).

Table 2. Supply Chain and Resource Impacts

Resource/Material	Global Use in Digital Devices (%)	Environmental Impacts	Projected Shortages by 2060	Mitigation Strategies
Terbium (REE)	55% per capita mineral capacity	GHG emissions 1.4–5.9%, water pollution, soil degradation	2–5× current shortage	Green mining, recycling, secondary sourcing
Gold	55% of e-circuit extraction	Habitat loss, toxic emissions	Stable	Urban mining, modular devices
Rare Earth Elements (General)	N/A	Water use, energy demand, toxic waste	N/A	Circular economy, policy frameworks

This body of evidence underscores the necessity of integrating circular economy principles into digital supply chains to decouple technological growth from resource depletion and environmental degradation (Aslan *et al*., 2024; Istrate *et al*., 2024).

Emerging risks from AI and cloud computing

Artificial intelligence (AI) and cloud computing represent emerging frontiers of digital environmental risk, intensifying energy consumption, water use, and electronic waste generation as largely invisible pollutants. The rapid expansion of AI-driven data centers is projected to significantly increase emissions. In the United States alone, AI servers could emit between 24 and 44 million tons of CO_2-equivalent annually by 2030, while consuming up to 1,125 million cubic meters of water for cooling purposes (Virmani, 2025). At a global level, AI's environmental footprint includes substantial energy demands for model training, continuous data storage, and frequent hardware replacement cycles, contributing further to e-waste accumulation (Li *et al*., 2025).

The literature presents a nuanced assessment of AI's dual role. On one hand, AI offers substantial benefits for sustainability, including energy optimization, climate modeling, predictive maintenance, and resource-efficient logistics (Goel *et al*., 2024; Li *et al*., 2025). On the other hand, rebound effects and increased digital consumption risk offsetting these gains. Within green value chains, AI enhances efficiency across upstream material sourcing, midstream logistics, and downstream recycling processes. However, persistent challenges include fragmented data infrastructures, lack of transparency, and the growing environmental cost of AI computation itself (Goel *et al*., 2024).

Additional risks associated with AI deployment include algorithmic bias, lack of explainability, governance gaps, and the potential widening of socio-economic inequalities (Li *et al*., 2025). From a thematic perspective, achieving net-zero digital pathways requires substantial improvements in energy efficiency, which could reduce emissions by up to 73%, alongside strategic data center location planning and accelerated decarbonization of electricity grids (Virmani, 2025). Future research and policy directions emphasize the development of Green AI, ethical governance frameworks, and integration with emerging technologies such as blockchain to enable transparent, accountable, and sustainable digital supply chains (Goel *et al*., 2024; Li *et al*., 2025).

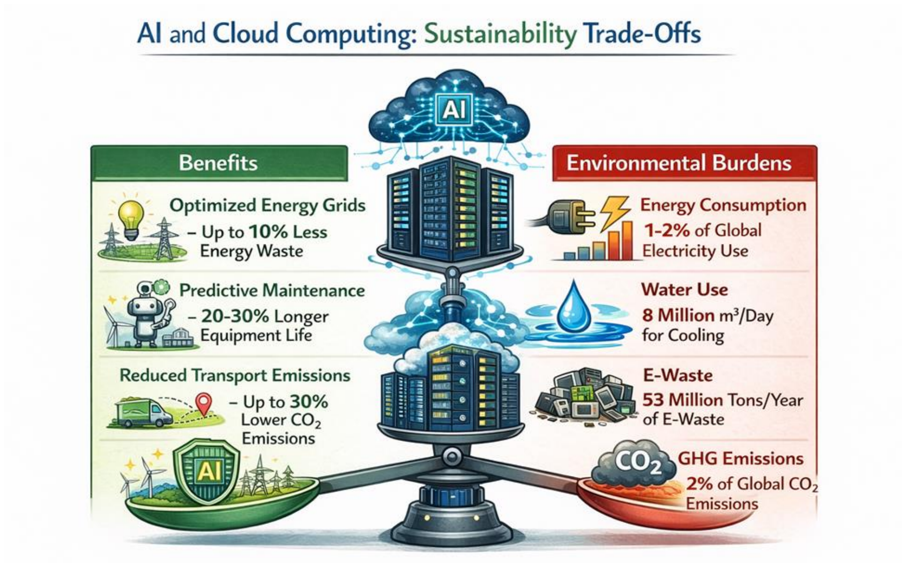

Figure 2. AI and Cloud Computing Environmental Impacts

Overall, this section highlights the paradoxical nature of AI and cloud computing as both enablers of sustainability and sources of emerging environmental pollutants, underscoring the necessity of responsible innovation and coordinated regulation (Goel *et al*., 2024; Virmani, 2025).

RESULTS AND DISCUSSION

The thematic exploration in this review illuminates the multifaceted environmental risks posed by digitalization and data infrastructure, framing them as invisible pollutants that permeate global ecosystems. Data centers, as central hubs of digital activity, exemplify this paradigm through their voracious energy consumption and associated carbon emissions (Manganelli *et al*., 2021; Mytton, 2021; Khan *et al*., 2025). Studies consistently demonstrate that inefficiencies in cooling and power usage exacerbate GHG outputs, with regional disparities highlighting how reliance on fossil fuels amplifies these impacts (Aslan *et al*., 2024; Xiao *et al*., 2025). For instance, the integration of AI servers in the United States is projected to escalate emissions unless mitigated by renewable transitions, underscoring the pollutant-like behavior of unchecked energy demands (Xiao *et al*., 2025). This synthesis reveals a consensus in the literature: while digital infrastructure drives innovation, its environmental footprint rivals traditional industries, necessitating a reevaluation of sustainability metrics (Hultström *et al*., 2023; Istrate *et al*., 2024; de Vries-Gao, 2025). Water usage emerges as a critical yet underappreciated dimension of digital pollution, where data centers' cooling requirements deplete resources in vulnerable regions (Mytton, 2021; de Vries-Gao, 2025). The carbon-water nexus, as articulated in recent analyses, shows that indirect water footprints from electricity generation dominate, potentially straining supplies equivalent to millions of households (de Vries-Gao, 2025). Mitigation strategies, such as advanced cooling technologies and site selection in water-abundant areas, offer promising reductions, but implementation lags due to economic priorities (Mytton, 2021; Xiao *et al*., 2025). This theme intersects with broader resource depletion, including rare earth minerals essential for hardware, where supply chain vulnerabilities perpetuate environmental degradation through mining pollution and geopolitical tensions (Goel *et al*., 2024). The literature suggests that circular approaches could alleviate these pressures, yet gaps in global cooperation hinder progress (Ribiere, 2021; Jain *et al*., 2023).

Digital and electronic waste further compound these risks, manifesting as toxic pollutants that leach into environments and pose health threats (Shevchenko *et al*., 2019; Jain *et al*., 2023). Reviews indicate that informal recycling dominates in developing regions, releasing hazardous substances and contributing to GHG emissions from improper disposal (Jain *et al*., 2023). Framing digital waste as a pollutant extends beyond physical e-waste to include data redundancies that sustain unnecessary energy use, a novel perspective that integrates intangible digital elements into environmental discourse (Shevchenko *et al*., 2019; Pricopoaia *et al*., 2025). Supply chain analyses reveal upstream impacts, with rare earth extraction driving habitat loss and emissions, emphasizing the need for diversified sourcing and recycling to disrupt this cycle (Goel *et al*., 2024).

The advent of AI and cloud computing intensifies these pollutants, with energy-intensive models challenging net-zero ambitions (Aslan *et al*., 2024; Khan *et al*., 2025; Virmani, 2025). While AI enables environmental optimizations, its own footprint—encompassing emissions, water, and waste—creates a rebound effect that literature warns could undermine sustainability gains (Li *et al*., 2025; Xiao *et al*., 2025). Green AI techniques, such as efficient algorithms and hardware, present viable pathways, but require interdisciplinary collaboration to scale (Khan *et al*., 2025).

Implications of these findings are profound for policy and practice. Treating digital elements as pollutants fosters regulatory frameworks that internalize externalities, such as carbon pricing for data centers or mandates for e-waste recycling (Manganelli *et al*., 2021; Istrate *et al*., 2024). However, limitations in the reviewed literature include a focus on developed nations, with scant data from emerging economies where digital growth is rapid (Jain *et al*., 2023; Oo *et al*., 2023). Methodological inconsistencies in footprint assessments—varying scopes for emissions and water—complicate comparisons, suggesting a need for standardized metrics (Mytton, 2021; de Vries-Gao, 2025). Moreover, the rapid evolution of technologies like AI outpaces research, creating uncertainties in projections (Aslan *et al*., 2024; Xiao *et al*., 2025). Interdisciplinary integration is crucial, bridging environmental science with informatics to address these gaps. Economic incentives, such as subsidies for renewable-powered infrastructure, could accelerate transitions, while public awareness campaigns highlight the hidden costs of digital consumption (Li *et al*., 2025; Pricopoaia *et al*., 2025). Ultimately, this review posits that sustainable digitalization demands a paradigm shift: viewing data not as an infinite resource but as a pollutant requiring careful management to align with planetary limits (Shevchenko *et al*., 2019).

CONCLUSION

In conclusion, this narrative review underscores the emergence of invisible pollutants from digitalization and data infrastructure, encompassing data centers' energy and water demands, digital waste streams, and supply chain impacts. By synthesizing evidence from 2019-2025 literature, we highlight how these elements contribute to climate change, resource scarcity, and ecological harm, while proposing mitigation through efficiency, circularity, and policy innovation. The novelty lies in reconceptualizing digital artifacts as pollutants, fostering a holistic approach to sustainability.

Future directions include empirical studies on underrepresented regions, development of unified assessment frameworks, and exploration of emerging technologies like edge computing for reduced centralization. Longitudinal research on AI's net environmental effects, coupled with international collaborations for e-waste governance, will be pivotal. Policymakers should prioritize incentives for green digital practices, ensuring technological advancement supports rather than undermines environmental goals. Through these efforts, digitalization can evolve from a risk to a catalyst for sustainability.

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