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(Research Article)

Green computing techniques for eco-friendly digital transformation in developing economies

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Abstract

The rapid proliferation of computing technologies, cloud infrastructure, and Internet of Things (IoT) devices has intensified global energy consumption, accelerated electronic waste generation, and amplified greenhouse gas emissions. These trends pose acute sustainability challenges, particularly for developing economies in Sub-Saharan Africa where power infrastructure remains unreliable, e-waste governance frameworks are nascent, and financial resources for green technology adoption are severely constrained. This paper presents a comprehensive review of green computing techniques and examines their potential to create environmentally sustainable computing environments in developing economies. Drawing on a structured review of peer-reviewed literature published between 2010 and 2024, the study analyses key green computing dimensions including energy-efficient data center design, server virtualization, cloud resource optimization, e-waste lifecycle management, green procurement, AI-driven power management, and renewable energy integration. The findings reveal that, while significant adoption gaps persist in low-income settings, targeted policy interventions, capacity-building programmes, and south-south technology transfer partnerships can substantially advance green computing uptake. The study concludes that green computing is not a luxury exclusive to technologically advanced nations but a strategic imperative for developing economies seeking to leapfrog legacy, energy-intensive ICT infrastructure and achieve sustainable digital development.

Keywords: Green Computing; Green IT; Cloud Computing; Energy Efficiency; Data Centers; Environmental Sustainability; Virtualization; E-waste; Renewable Energy; Developing Economies; Sub-Saharan Africa; ICT Sustainability

1. Introduction

The accelerating digitisation of economies worldwide has placed unprecedented pressure on Information and Communication Technology (ICT) infrastructure. Global data center electricity consumption is estimated to account for approximately 1–2% of total worldwide electricity use, with projections indicating that this figure could rise sharply as artificial intelligence workloads, big data analytics, and IoT deployments intensify [1]. Large-scale data center facilities, integrating thousands of servers alongside their associated cooling, storage, and networking systems, are operated by corporations including Google, Amazon, Microsoft, and Meta, each consuming energy at scales comparable to small cities. The environmental footprint of these installations—measured in carbon emissions, water consumption, and electronic waste—has made ICT sustainability one of the defining technology policy challenges of the twenty-first century. Figure 1 below illustrates the operational dynamics of cloud data centers and the environmental challenge they present, alongside the green computing solution pathway.

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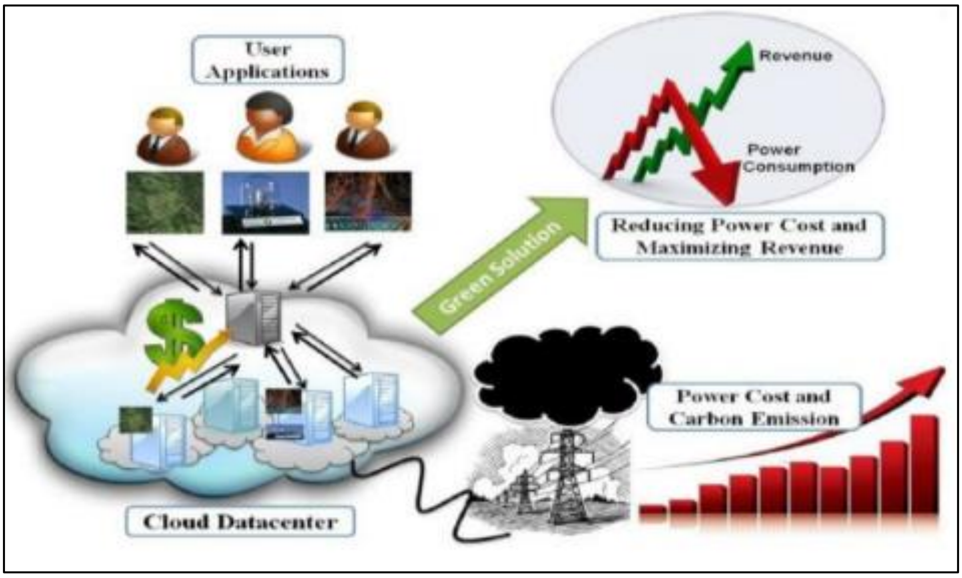

Figure 1 Cloud Data Center Operations — The Dual Challenge of Power Cost and Carbon Emission, and the Green Solution Pathway

As shown in Figure 1, cloud data centers serve diverse user applications while simultaneously driving up power consumption and carbon emissions. The diagram underscores the central argument of this paper: that green computing interventions — from renewable energy integration to workload optimization — can reverse the upward trend in power cost and carbon output, enabling data centers to reduce their environmental footprint while maintaining or improving operational revenue. Cloud computing—the delivery of on-demand computing resources as a utility on a pay-as-you-go basis—has catalyzed the transition from ownership-based infrastructure to scalable, subscription-driven service models [2]. According to the International Energy Agency (IEA), data centers consumed an estimated 200–250 TWh of electricity globally in 2022 [3].

The sustainability challenge is particularly acute in developing economies across Africa, South Asia, and Latin America, where rapid ICT adoption is occurring against a backdrop of unreliable power grids, limited renewable energy penetration, weak e-waste legislation, and constrained institutional capacity. Countries such as Kenya, Nigeria, Ghana, and Rwanda are experiencing significant growth in mobile internet adoption, cloud service consumption, and data center investment, yet lack the regulatory frameworks, technical expertise, and financial instruments needed to ensure that this growth is ecologically sustainable. This paper addresses this underexplored intersection between green computing and developing-economy contexts, arguing that green computing techniques must be contextualised and adapted rather than simply transplanted from high-income settings. The study is guided by the following objectives: (i) to review established green computing techniques and their documented effectiveness; (ii) to assess the specific barriers and opportunities for green computing adoption in developing economies; (iii) to synthesize evidence-based recommendations for policymakers, institutions, and industry actors in low-income settings.

2. Literature review

The academic discourse on green computing has evolved substantially over the past two decades, transitioning from largely definitional and conceptual contributions to empirical assessments of specific technologies and policy instruments. Murugesan [4] is widely credited with establishing the foundational taxonomy of green IT, articulating four interdependent dimensions—green use, green disposal, green design, and green manufacturing—that remain the organizing framework for most subsequent scholarship. Green computing, under this framework, is anchored in the triple bottom line of economic viability, social responsibility, and environmental stewardship [4], as illustrated in Figure 2. The conceptual foundation of green computing is best understood through the triple bottom line framework, as depicted in Figure 2 below.

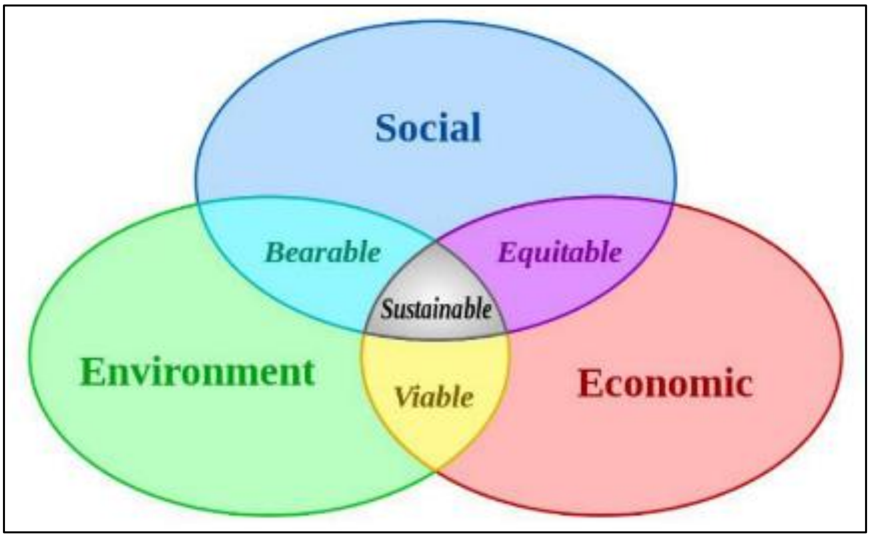

Figure 2 The Triple Bottom Line of Sustainability — The Intersection of Social, Environmental, and Economic Dimensions that Defines Sustainable ICT Practice

Figure 2 illustrates the three mutually reinforcing pillars that underpin green computing: environmental stewardship, social responsibility, and economic viability. True sustainability, represented at the center of the Venn diagram, is achieved only where all three dimensions intersect simultaneously. In the context of ICT in developing economies, this means that green computing strategies must not only reduce carbon emissions and e-waste (environmental), but must also be financially viable for resource-constrained institutions (economic), and must protect communities from the hazards of informal e-waste processing while expanding equitable access to clean digital infrastructure (social). Building on this foundation, Tomlinson [5] examined the systemic environmental costs of computing, demonstrating that lifecycle emissions from hardware manufacturing frequently exceed those associated with operational energy consumption — a finding with important implications for procurement policy in developing economies where imported second-hand equipment dominates the ICT market.

Belkhir and Elmeligi [6] provided one of the most cited quantitative analyses of ICT's carbon footprint, estimating that the sector accounts for approximately 3.5% of global greenhouse gas emissions and warning that this share could double by 2025 absent aggressive efficiency interventions. Their work highlighted the growing contribution of consumer devices and wireless networks relative to data centers, a dimension often overlooked in infrastructure-centric reviews. Shuja et al. [7] subsequently synthesized techniques for greening emerging IT domains—cloud computing, mobile computing, big data, and IoT—and identified cross-cutting research gaps including the absence of standardized energy benchmarking methodologies and the inadequacy of existing regulatory frameworks to incentivize vendor compliance.

Literature specifically addressing green computing in developing-economy contexts is sparser, though a growing body of work has begun to address this gap. Osibanjo and Nnorom [8] documented the scale of e-waste flows into West African countries, noting that informal recycling practices expose workers and surrounding communities to severe toxic hazards while simultaneously representing a missed opportunity for material recovery. Heeks et al. [9] argued that the dominant green computing agenda—shaped largely by Western regulatory contexts and corporate priorities—is poorly calibrated to the realities of low-income settings, where energy access, hardware affordability, and institutional capacity present fundamentally different constraints. Nkohkwo and Islam [10] reviewed mobile broadband adoption across Africa and observed that the region's leapfrogging trajectory—bypassing fixed-line infrastructure in favour of wireless connectivity—creates both an opportunity and a responsibility to embed energy efficiency norms from the outset of infrastructure deployment.

3. Methods

This study employs a structured literature review methodology, following the principles of systematic evidence synthesis adapted for ICT sustainability research. The review protocol was designed to ensure transparency, reproducibility, and comprehensiveness in the identification and analysis of relevant literature. A comprehensive search was conducted across four major academic databases: IEEE Xplore, ACM Digital Library, Scopus, and Google Scholar. The search terms applied included combinations of: "green computing", "green IT", "sustainable ICT", "energy-efficient data centers", "e-waste developing economies", "cloud computing sustainability", "ICT carbon footprint", "virtualization energy savings", and "green computing Africa". The search was restricted to publications between January 2010 and December 2024 to capture the contemporary state of the field while ensuring sufficient historical depth to track the evolution of key concepts.

Studies were included if they: (i) were published in peer-reviewed journals, conference proceedings, or reputable institutional reports; (ii) addressed green computing techniques, ICT energy consumption, e-waste management, or related sustainability dimensions; and (iii) provided empirical evidence, analytical frameworks, or substantive policy analysis. Studies were excluded if they were purely theoretical without grounding in evidence, published in predatory journals, or addressed ICT sustainability in contexts entirely disconnected from cloud computing, data centers, mobile computing, big data, or IoT. Grey literature—including reports from the IEA, OECD, African Union, and United Nations Environment Programme—was included where it provided data or policy frameworks not available in peer-reviewed sources.

From an initial pool of 214 sources identified through database searches, 87 were retained after title and abstract screening, and 43 were included in the final synthesis following full-text review. Data were extracted against a structured template covering: (i) green computing technique(s) addressed; (ii) geographic and sectoral context; (iii) key quantitative findings where reported; (iv) barriers and enablers identified; and (v) policy or practice recommendations. A narrative synthesis approach was adopted, given the heterogeneity of study designs and contexts, with findings organised thematically around the paper's primary research objectives.

4. Findings

The findings are organised around four thematic areas: (i) green computing techniques and their documented effectiveness; (ii) the specific challenges facing developing economies; (iii) the environmental and economic impact of green computing adoption; and (iv) emerging trends shaping the future of the field.

4.1. Green Computing Techniques and Their Effectiveness

The review identified seven principal green computing techniques with documented effectiveness across multiple deployment contexts.

Energy-efficient data center design represents the most structurally impactful intervention. The Power Usage Effectiveness (PUE) metric—the ratio of total facility energy to IT equipment energy—has emerged as the standard benchmark for data center efficiency. Hyperscale operators such as Google and Meta have achieved PUE values approaching 1.1, compared to an industry average of approximately 1.58 [1]. Techniques contributing to this improvement include hot/cold aisle containment, free cooling using ambient air or water, liquid immersion cooling, and modular data center designs that enable precise capacity matching [11].

Server virtualization enables server consolidation ratios of 10:1 or higher, dramatically reducing the physical server footprint and associated energy draw for both computation and cooling [15]. Hypervisor platforms including VMware vSphere, Microsoft Hyper-V, and the open-source KVM enable dynamic workload migration, allowing underutilized servers to be powered down during off-peak periods. Energy savings of 30–50% following virtualization deployments in enterprise data centers have been consistently reported [7].

AI-driven power management represents a rapidly advancing frontier. Google's DeepMind team demonstrated a 40% reduction in data center cooling energy through reinforcement learning-based control systems, achieving a corresponding 15% reduction in overall PUE [16]. AI-based workload schedulers can dynamically shift processing to time slots aligned with renewable energy availability or low-carbon grid periods. For developing economies where advanced AI infrastructure is nascent, lighter-weight approaches including dynamic voltage and frequency scaling (DVFS) and adaptive cooling control offer immediately deployable efficiency gains.

E-waste lifecycle management addresses the disposal dimension of green computing. The Basel Convention's technical guidelines and the European Union's WEEE Directive provide internationally recognised frameworks for responsible e-waste handling, though adherence remains inconsistent in developing-economy contexts [8]. Producer responsibility schemes, in which manufacturers bear financial responsibility for end-of-life equipment collection and recycling, have been implemented in approximately 67 countries, with variable effectiveness depending on enforcement capacity [13].

Telecommuting and digital workplace solutions reduce transport-related emissions while simultaneously decreasing demand for office energy consumption. Studies report that remote work arrangements can reduce individual carbon footprints by 54% compared to office-based work, though network and device energy consumption partially offsets these gains [9].

Green procurement—prioritizing the purchase of Energy Star-labelled and EPEAT-registered products—enables organizations to embed sustainability criteria into standard procurement cycles. The Electronic Product Environmental Assessment Tool (EPEAT) evaluates products against 51 environmental criteria spanning energy efficiency, materials, end-of-life management, and supply chain accountability [13].

Renewable energy integration, including on-site solar installations and off-site Power Purchase Agreements (PPAs), enables data centers and ICT facilities to reduce their grid carbon intensity. Microsoft, Google, and Amazon have committed to 24/7 carbon-free energy matching—ensuring that every unit of electricity consumed is matched by renewable generation in the same grid zone at the same hour [20].

4.2. Green Computing Challenges in Developing Economies

The review identified a distinct set of structural barriers to green computing adoption in developing economies that diverge significantly from those documented in high-income settings.

Energy infrastructure constraints are the most fundamental. Unreliable grid electricity forces organizations to rely on diesel generators for backup power, negating potential energy savings from efficiency measures and adding substantially to operational carbon emissions. In Sub-Saharan Africa, average electricity access rates remain below 50% in several countries, and supply reliability is a chronic challenge even in urban centers [1].

Financial constraints limit access to green technologies. Energy-efficient servers, advanced cooling systems, and solar installations carry higher upfront capital costs that are frequently beyond the budgets of SMEs, public institutions, and government agencies in low-income settings. The absence of green technology financing instruments—such as concessional loans, green bonds, or equipment leasing schemes—further restricts adoption.

Regulatory and institutional gaps mean that e-waste legislation is either absent, inadequately enforced, or insufficiently aligned with international standards across much of the developing world. The dominance of informal e-waste processing—particularly in Ghana's Agbogbloshie district and Nigeria's Lagos state—exposes workers to severe toxic hazards while preventing the recovery of valuable materials including gold, copper, and palladium [8].

Technical capacity deficits reduce the pool of professionals capable of designing, deploying, and maintaining green computing systems. University ICT curricula in many developing economies have yet to integrate energy efficiency and sustainability as core competencies, reflecting broader gaps in environmental awareness within the technology sector.

However, the review also identified significant opportunities. Kenya's electricity grid—over 90% renewable, primarily from geothermal and hydro sources—provides a distinctly low-carbon foundation for data center operations, making green data center investment in Nairobi particularly attractive relative to fossil-fuel-dependent grid environments [17]. Rwanda's national ICT strategy and Kigali's emergence as a regional technology hub demonstrate that coordinated policy ambition can accelerate sustainable ICT development even in resource-constrained settings.

4.3. Environmental and Economic Impact of Green Computing

The adoption of green computing principles generates measurable impacts across environmental, economic, and social dimensions. Environmentally, large-scale data center virtualization and consolidation projects have been demonstrated to reduce facility-level carbon emissions by 30–60%, depending on baseline infrastructure and grid carbon intensity [7]. At the global scale, the IEA estimates that data center energy intensity per unit of compute output has improved by approximately 20% annually over the past decade, driven primarily by hardware efficiency gains and workload optimization [1].

Economically, energy costs represent 40–70% of total data center operating expenditure; efficiency improvements therefore translate directly into improved financial sustainability for both commercial operators and public institutions [3]. For developing-economy organizations operating on constrained budgets, these savings can be reinvested in expanded ICT access, skills development, or service delivery improvements.

At the societal level, formalized e-waste recycling programmes create employment in the green economy while protecting communities from toxic hazards. Reduced reliance on diesel generators—through more energy-efficient primary systems and solar-powered alternatives—improves air quality in urban areas. Performance-Optimized Data Centers (PODs) provide scalable, modular solutions enabling colocation providers and telecommunications companies to expand capacity in an energy-efficient manner without the capital intensity of bespoke facility construction [18].

4.4. Emerging Trends

ARM-based server architectures—exemplified by Amazon's Graviton and Ampere's Altra processors—have demonstrated substantial performance-per-watt improvements relative to legacy x86 designs, enabling meaningful energy reductions for cloud workloads [19]. The development of energy-proportional computing—where systems consume power in direct proportion to their utilisation—represents a further structural advancement that reduces the baseline energy draw of idle servers.

The field of Sustainable AI is gaining prominence as the energy costs of training large language models and other foundation models attract scrutiny. Training GPT-3, for example, was estimated to consume approximately 1,287 MWh of electricity and emit 552 tonnes of CO2 equivalent [6]. As AI adoption accelerates across developing economies, embedding energy efficiency requirements into national AI strategies from the outset is critical to avoiding the replication of high-carbon AI infrastructure patterns currently observable in high-income economies.

South-south technology partnerships offer a promising modality for accelerating green computing uptake in developing economies. Bilateral and multilateral arrangements that facilitate the transfer of regulatory frameworks, technical expertise, and procurement consortia have demonstrated potential in regional fora, including the East African Community and ECOWAS, where harmonized e-waste legislation and shared green procurement standards could leverage collective bargaining power, vis-à-vis technology vendors.

5. Discussion

The findings of this review illuminate several tensions and opportunities that warrant sustained analytical attention. A central tension exists between the global trajectory of green computing—driven overwhelmingly by the priorities and resources of hyperscale cloud operators in high-income economies—and the distinct needs of institutions, enterprises, and governments in developing economies. The risk is that green computing discourse and practice remain captured by a small number of highly capitalized actors whose solutions, while technically impressive, are neither affordable nor practically deployable in lower-resource contexts.

This is not to suggest that the achievements of hyperscale operators are irrelevant to developing economies. The widespread adoption of cloud services in Africa, Asia, and Latin America means that many users in developing economies are already, indirectly, beneficiaries of the energy efficiency improvements implemented in hyperscale facilities. A Kenyan SME hosting its applications on a cloud provider's African region benefits from the PUE improvements and renewable energy commitments of that provider, even if the SME itself has neither the awareness nor the agency to make green procurement decisions independently. Cloud migration can thus be understood as an accessible entry point into green computing for developing-economy organizations.

However, the review also reveals that cloud migration alone is insufficient. The e-waste challenge is not ameliorated by cloud adoption—if anything, the rapid proliferation of endpoint devices driven by growing internet access accelerates the volume of end-of-life hardware requiring responsible management. Similarly, the energy consumed by mobile networks and user devices—which account for a growing share of total ICT energy consumption globally—is not addressed by data center efficiency measures alone. A comprehensive green computing strategy for developing economies must therefore span the full ICT value chain, from device manufacturing and procurement through operational efficiency to end-of-life management.

The role of government policy emerges from the review as a critical enabling factor. Jurisdictions where government has established clear regulatory frameworks, fiscal incentives, and institutional capacity for green ICT—such as Rwanda's National ICT Policy and Kenya's National Energy Efficiency and Conservation Strategy—demonstrate measurably better outcomes than those where policy frameworks are absent or unenforced. This finding is consistent with the broader green economy literature, which identifies government coordination as essential to overcoming the market failures that constrain voluntary green technology adoption.

Finally, the review highlights the importance of local capacity building. Technical solutions imported wholesale from high-income contexts frequently fail in practice due to incompatibility with local infrastructure, insufficient technical skills for operation and maintenance, and misalignment with local regulatory and cultural contexts. Green computing education and training programmes—embedded within university ICT curricula and TVET institutions—are a prerequisite for sustainable adoption at scale.

6. Conclusion

This paper has presented a comprehensive review of green computing techniques and their relevance to the creation of environmentally sustainable computing environments in developing economies. Across the dimensions of energy-efficient data center design, server virtualization, AI-driven workload optimization, e-waste lifecycle management, green procurement, renewable energy integration, and regulatory governance, a consistent finding emerges: the technical solutions to reduce ICT's environmental footprint are available, proven, and increasingly cost-competitive. The primary barriers to adoption in developing economies are not technological but institutional, financial, and informational.

The study confirms that green computing is not a luxury exclusive to technologically advanced nations. Developing economies—particularly those with high renewable energy endowments, rapidly expanding ICT sectors, and strong policy ambition—are well positioned to leapfrog legacy, energy-intensive ICT infrastructure and build sustainable digital ecosystems aligned with the African Union's Digital Transformation Strategy and the United Nations Sustainable Development Goals. Realizing this potential requires sustained collaboration among governments, industry, academia, and civil society.

Recommendations

Based on the findings and discussion, the following recommendations are directed at key stakeholder groups:

- For Governments and Policymakers

National governments in developing economies should establish mandatory green ICT strategies that set measurable energy efficiency targets for public sector data centers, government ICT procurement, and telecom infrastructure. Fiscal incentives—including tax relief on energy-efficient equipment purchases, import duty waivers on solar panels for ICT facilities, and preferential public procurement for EPEAT-registered products—should be instituted to stimulate private sector adoption. Harmonized e-waste legislation, aligned with the Basel and Stockholm Conventions, should be enacted and enforced with sufficient institutional capacity, including trained inspectors and certified recycling facilities.

- For Educational Institutions

Universities and technical and vocational education and training (TVET) institutions should integrate green computing competencies—spanning energy-efficient system design, e-waste management, and ICT lifecycle assessment—into core ICT and engineering curricula. Research programmes focused on the contextualization of green computing for developing-economy conditions should be established and funded, generating locally relevant evidence to inform policy and practice. Partnerships between African universities and international research institutions can accelerate knowledge transfer while building indigenous research capacity.

- For Industry and the Private Sector

ICT vendors operating in developing-economy markets should make energy efficiency data—including PUE, carbon intensity, and product lifecycle assessments—readily available to customers, enabling informed green procurement decisions. Telecommunications operators should commit to renewable energy targets for their network infrastructure, leveraging the favourable renewable energy endowments available in many African markets. Colocation and cloud service providers should offer green data center options—including carbon-neutral hosting and renewable energy certificates—at price points accessible to SMEs and public institutions.

- For Regional and International Bodies

The African Union, ECOWAS, the East African Community, and SADC should pursue harmonized regional frameworks for green ICT procurement, e-waste management, and data center energy efficiency standards. Development finance institutions—including the African Development Bank, the World Bank, and bilateral development finance institutions—should expand concessional financing facilities for green data center infrastructure and renewable energy integration in ICT facilities. South-south technology partnerships that facilitate the sharing of regulatory frameworks, technical expertise, and procurement consortia should be actively supported and funded as a complement to traditional north-south technology transfer.

- For Future Research

Several research gaps identified by this review warrant attention from the academic community. First, empirical studies measuring the actual energy savings achieved by green computing interventions in developing-economy data centers are scarce; longitudinal case studies from East and West African contexts would substantially advance the evidence base. Second, the equity implications of green computing—including the distributional impacts of e-waste formalization on informal sector workers and the differential access of small versus large enterprises to green technologies—deserve dedicated investigation. Third, the intersection of Sustainable AI and developing-economy ICT infrastructure represents an urgent and underexplored research frontier.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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