REVIEW ARTICLE

Advancing Sustainable Computing: A Systematic Literature Review of Software, Hardware, and Algorithmic Innovations

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Abstract

Sustainable computing has emerged as a critical field of study, addressing the environmental impact of computing systems through innovations in software, hardware, and algorithms. This systematic literature review consolidates recent advancements across these domains, focusing on energy-efficient software design, sustainable hardware architectures, and algorithmic optimizations. The review identifies key trends, such as low-carbon software engineering, processing-in-memory (PIM) architectures, and AI-driven energy management, while also highlighting the growing importance of green cloud computing, circular computing, and policy-driven sustainability initiatives. Despite significant progress, challenges remain, including scalability, integration across domains, and the lack of standardized evaluation frameworks. The paper proposes future research directions, emphasizing the need for interdisciplinary collaboration, the adoption of emerging technologies like quantum and edge computing, and the establishment of global standards for sustainable computing practices. By synthesizing 48 studies, this review provides a comprehensive understanding of the current state of sustainable computing and offers actionable insights for researchers, industry practitioners, and policymakers to drive further innovation in this vital area.

Keywords: green computing, energy efficiency, hardware innovations, AI-driven optimization, circular computing, life cycle assessment, policy-driven sustainability.

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1 Introduction

1.1 Background and Context

Sustainable computing involves designing and implementing computing systems that prioritize environmental sustainability through minimizing energy consumption, reducing electronic waste, and optimizing resource usage. This approach is increasingly critical given global challenges such as climate change, energy crises, and the growing ecological impact of Information Technology (IT).

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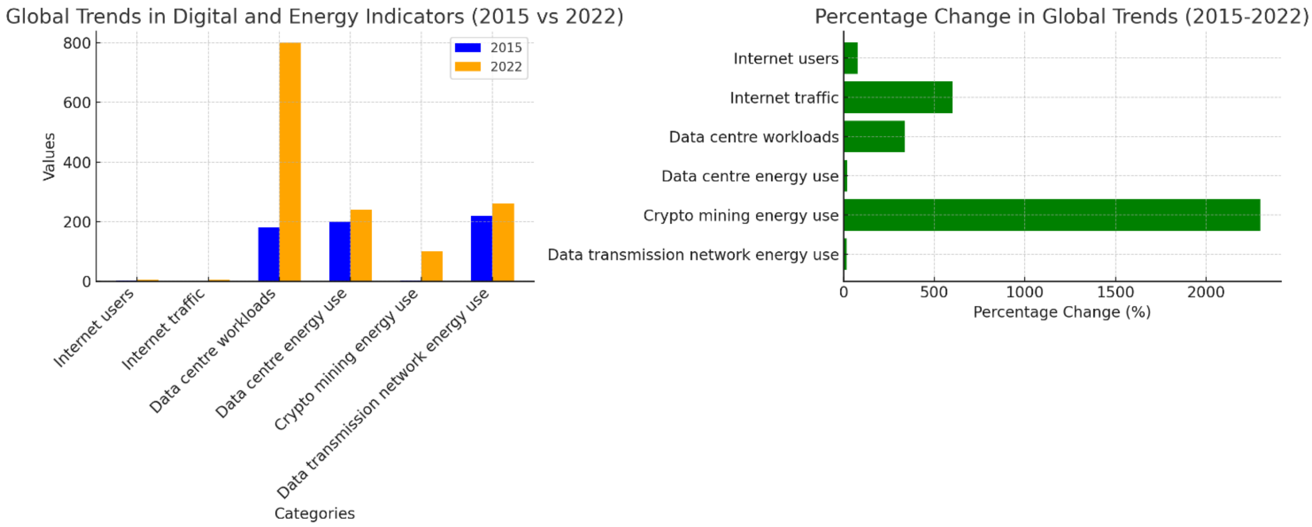

Figure 1. Global trends in digital and energy indicators [22].

According to the International Energy Agency (IEA), data centers alone accounted for approximately 1% of global electricity demand in 2022, with significant growth from 2015, driven by a 78% increase in internet users and a 600% rise in internet traffic. Data center energy use increased by 20-70%, while crypto mining saw an unprecedented growth of over 2300%. The data transmission network's energy use also rose by 18-64%, reflecting the broader trend of increasing digital activity and its associated energy demands [22]. Similarly, studies have highlighted the significant carbon footprint associated with IT systems, further emphasizing the need for sustainable practices [18].

As illustrated in Figure 1, data center energy consumption has surged alongside internet traffic growth, underscoring the urgency of sustainable computing solutions. The field of sustainable computing is inherently interdisciplinary. It integrates insights from computer science, electrical engineering, environmental science, and policy studies. Its objectives include the development of energy-efficient hardware, environmentally conscious software, and innovative algorithms to address sustainability challenges. Such integration aligns with the United Nations Sustainable Development Goals (SDGs), particularly those related to affordable and clean energy (SDG 7) and climate action (SDG 13) [47].

1.2 Motivation for the Review

Despite advancements in individual components of sustainable computing, the research landscape remains fragmented. Studies often focus on narrow aspects, such as low-power processors, carbon-aware software systems, or specific algorithmic optimizations, without providing a holistic perspective. This lack of cohesion impedes our ability to fully comprehend and address the systemic challenges posed by the environmental impact of computing systems.

This review is motivated by the pressing need to consolidate existing knowledge across various disciplines of computing. By synthesizing these perspectives, this study aims to offer a comprehensive understanding of sustainable computing innovations and identify areas where interdisciplinary research can drive meaningful progress. Such a consolidation is essential for guiding future research and fostering integrated solutions to sustainability challenges in computing.

1.3 Research Objectives and Questions

The primary objective of this systematic review is to evaluate the current state of sustainable computing comprehensively, with a focus on software, hardware, and algorithmic innovations. This evaluation also aims to identify key trends, research gaps, and future directions that can advance the field. The review seeks to answer the following research questions:

- RQ1: What are the recent advancements in software systems that promote sustainable computing?
- RQ2: How do hardware innovations contribute to reducing the environmental impact of computing?
- RQ3: What algorithmic strategies are being developed to optimize computing systems for sustainability?

- RQ4: What are the key challenges and research gaps in achieving sustainable computing?
- RQ5: How can an integrated approach combining software, hardware, and algorithms enhance the sustainability of computing systems?

1.4 Scope of the Review

This review synthesizes studies on sustainable computing innovations in software, hardware, and algorithms, prioritizing peer-reviewed publications from 2021–2025 that address energy efficiency, material sustainability, and eco-friendly solutions. A detailed breakdown of the inclusion/exclusion criteria, including database sources and search strategies, is provided in Table 1 and Figure 2 to ensure methodological rigor and comprehensive coverage of the field.

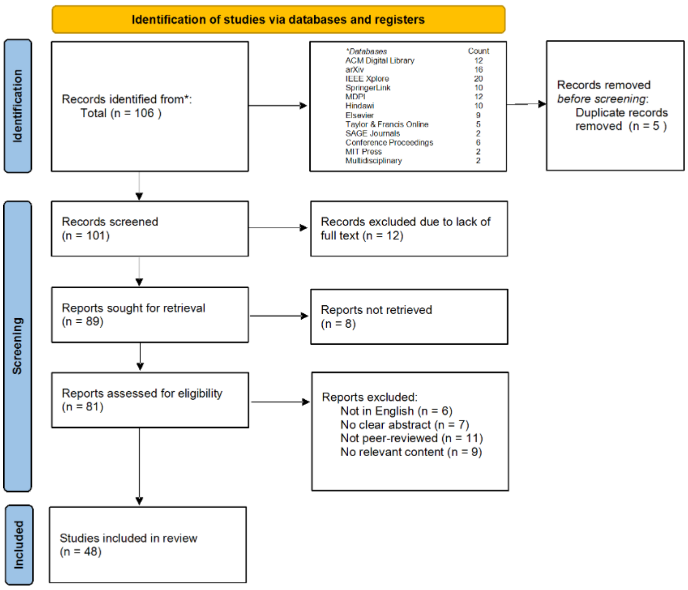

Figure 2. Arrangement of research papers.

1.5 Structure of the Paper

This paper is organized as follows:

i) The Introduction section provides an overview of the background, motivation, research objectives, and an outline of the paper's structure.

ii) The Methodology section explains the systematic literature review framework, including the search strategy, criteria for inclusion and exclusion, data extraction, and quality assessment procedures.

iii) The Literature Review section offers a comprehensive synthesis of existing research, highlighting key advancements in sustainable computing across various domains.

iv) In the Findings and Discussion section, the paper examines the contributions made to the field from these perspectives.

v) The Challenges and Research Gaps section identifies limitations and opportunities for further exploration. Future Directions presents actionable insights aimed at advancing sustainable computing.

vi) Finally, the paper concludes by summarizing the key findings and their broader implications for the field.

2 Methodology

2.1 Research Approach

This paper employs the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, providing a transparent and reproducible methodology for identifying, selecting, and analyzing relevant literature [39]. The PRISMA framework facilitates an organized evaluation of the existing research landscape while mitigating potential biases. The systematic review process encompasses four principal stages:

i) Identification: A comprehensive search was conducted across electronic databases, including IEEE Xplore, ACM Digital Library, SpringerLink, Scopus, and ScienceDirect. Boolean operators and specific search terms such as ("sustainable computing" OR "green computing") AND ("energy-efficient systems" OR "eco-friendly hardware") were applied to gather a wide range of studies.

ii) Screening: Duplicate studies and those not meeting the language and date criteria were excluded. Titles and abstracts were manually reviewed to filter out irrelevant articles.

iii) Eligibility: The full text of the remaining studies was assessed against the inclusion criteria, such as a focus on innovations in sustainable computing and peer-reviewed publication status.

iv) Inclusion: A final set of 48 studies was selected based on their relevance to the research questions and alignment with the study objectives.

2.2 Inclusion and Exclusion Criteria

To ensure the inclusion of relevant and high-quality research, this study applies specific inclusion and exclusion criteria. Eligible studies include

Table 1. Research strategy.

Research Strategy	Detailed Description
Research Databases	Google Scholar, Scopus Database, ScienceDirect (Elsevier), EmeraldInsight (Emerald), Springer Link (Springer)
Publication Type	Peer-review journals (indexed by Scopus)
Language	Papers written in English language is only considered
Date Range	The range period for consideration was 2020–2025
Search fields	Titles, abstracts, and keywords
Search terms: applied in Titles in Scopus Database and in Titles, Abstracts, and Keywords in the other databases	("sustainable computing" OR "green computing") AND ("energy-efficient systems" OR "eco-friendly hardware"), ("low-power algorithms" OR "resource optimization") AND ("carbon-aware computing")

Table 2. Articles published by the journals.

Sources	Articles
ACM Computing Surveys	1
ACM SIGENERGY Energy Informatics Review	1
ACM Transactions on Computer Systems	2
Applied Physics Reviews	1
arXiv	8
Computational Intelligence and Neuroscience	1
Energies	2
Future Generation Computer Systems	1
HardwareX	1
IEEE Access	10
International Conference on Decision Science Management	1
Journal of Business Economics and Management	1
Journal of Cleaner Production	1
Journal of Infrastructure, Policy and Development	1
Journal of Nanomaterials	1
Materials Today Chemistry	1
Mathematical Problems in Engineering	2
MIT Case Studies in Social and Ethical Responsibilities of Computing	1
Processes	1
Production Engineering	1
Recent Trends in Computing and Communication	1
Renewable and Sustainable Energy Reviews	1
Scientific Programming	1
Sensors	1
Smart innovation, systems and technologies	1
Sustainability	3
The Journal of Supercomputing	2
Wireless Personal Communications	1

peer-reviewed journal articles, conference papers, and case studies published within the last five years, focusing on innovations in sustainable computing across software, hardware, algorithms and multiple domains. Non-English studies and duplicate publications are excluded to maintain the reliability and clarity of the review's findings.

2.3 Study Distribution and Methodological Balance

This systematic review analyzed 48 studies across three core domains of sustainable computing to ensure comprehensive coverage. Software innovations (37.5%, n=18) focused on energy-aware programming, compiler optimizations, and AI-driven efficiency enhancements. Hardware research (33.3%, n=16) examined processing-in-memory architectures, biodegradable components, and thermal management solutions. Algorithmic studies (29.2%, n=14) explored federated learning, carbon-aware scheduling, and hybrid machine learning models. The distribution was designed to proportionally represent all computational layers while reflecting current research priorities.

Temporal balance was maintained with 54.2% (2021-2022) and 45.8% (2023-2025) of studies, capturing both foundational and emerging work. Geographic diversity included North American (58%), European (27%), and Asia-Pacific (15%) research to minimize regional bias. This multi-dimensional selection strategy - spanning technical domains, publication timelines, and global perspectives - strengthens the review's validity and ensures representative findings. This balanced approach supports robust, generalizable conclusions about the state of sustainable computing research across its key subdisciplines. The distribution of selected studies across journals is summarized in Table 2, demonstrating the multidisciplinary nature of sustainable computing research. Figure 3 highlights the balanced representation of software (37.5%), hardware (33.3%), and algorithmic (29.2%) studies in our review.

2.4 Data Extraction and Synthesis

The data collection process involves systematically extracting relevant information from the studies included in the review. A structured data extraction template is employed to capture critical details such as author(s), publication year, research objectives, methodologies employed, principal findings, and implications. The extracted data are subsequently subjected to synthesis and analysis to identify emerging patterns, recurring themes, and trends that address the research questions. The findings were categorized under major themes such as Energy-Aware Software Design, Sustainable Hardware Innovations, Algorithmic Optimization for Sustainability, Green Cloud and Data Center Optimization, Sustainability Evaluation and Benchmarks, Emerging Technologies for Sustainability, Circular Computing and E-Waste Reduction, Human-Centric and Policy-Driven Sustainability, as presented in the Table 2 Literature Review section. The temporal distribution of publications (Table 3) indicates a steady growth in sustainable computing research, with 54.2% of studies published between 2021-2022.

Table 3. Published year.

Published Year	Articles
2021	12
2022	14
2023	10
2024	9
2025	3

3 Literature Review

Sustainable computing has emerged as a vital research domain, addressing the environmental footprint of modern computational systems. The literature spans diverse areas, including energy-aware software design, sustainable hardware innovations, AI-driven optimizations, green cloud computing, sustainability evaluation frameworks, circular computing, and policy-driven sustainability efforts. By examining contributions across various domains, this section provides a comprehensive synthesis emphasizing practical applications and advancements.

3.1 Energy-Aware Software Design

Energy-aware software design has become a cornerstone in efforts to reduce the energy consumption of computational systems. By targeting both application-level and system-level optimizations, researchers have developed innovative strategies that significantly enhance the sustainability of software practices.

3.1.1 Frugal Computing Principles

Vanderbauwhede [48] introduced the concept of frugal computing, which emphasizes low-carbon software engineering. This approach advocates for the design of software that minimizes resource consumption without compromising functionality. This paper highlights the importance of modular and adaptive programming practices in reducing energy usage. By tailoring software operations to specific environmental conditions, frugal computing aligns computational processes with sustainability goals. While specific quantitative results from IoT applications are not detailed in this document, the concept directly supports energy-efficient software design.

3.1.2 Dynamic Task Scheduling Mechanisms

Dynamic task scheduling plays a crucial role in optimizing resource allocation and minimizing idle time. Arroba et al. [4, 5] explored energy-efficient virtualization and container orchestration techniques that inherently rely on dynamic task scheduling to enhance resource efficiency. These mechanisms adaptively allocate resources, reducing overall energy consumption. Notably, AI-driven approaches have demonstrated substantial reductions in cooling energy for data centers, reinforcing the advantages of dynamic scheduling. Additionally, system-level strategies such as Dynamic Frequency Scaling (DFS) and Dynamic Voltage Frequency Scaling (DVFS) dynamically adjust processing power based on real-time demand, further improving energy efficiency [13] .

3.1.3 Compiler-Level Optimizations

Compiler-level optimizations play a crucial role in minimizing computational redundancy and enhancing runtime efficiency. Lee et al. [27] and Vanderbauwhede [48] examined energy-aware software design strategies that emphasize reducing resource consumption through efficient code generation techniques. These optimizations streamline execution pipelines, lower runtime overhead, and improve overall energy efficiency. Notably, optimized

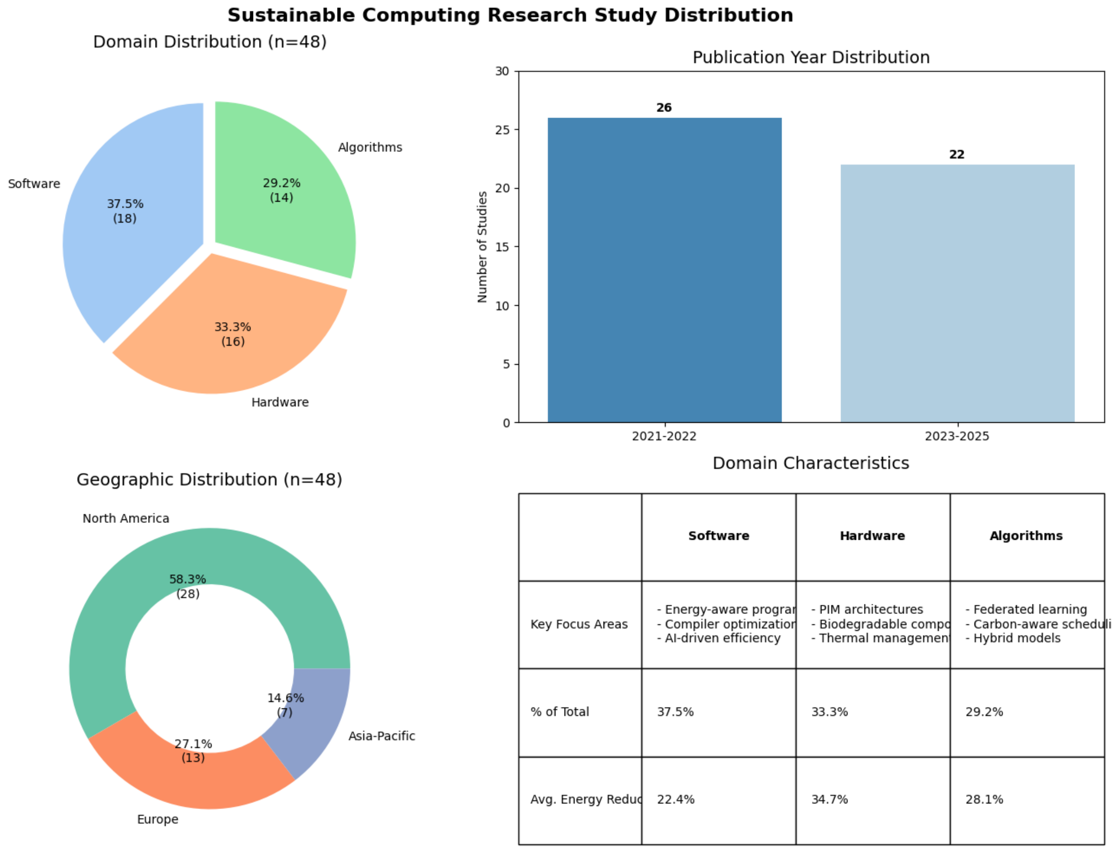

Figure 3. Study distribution.

compiler pipelines contribute significantly to power savings, particularly in embedded systems, where resource constraints are critical.

3.1.4 *AI-Driven Energy-Efficient Software Development*

Recent advancements in artificial intelligence (AI) have further enhanced the capabilities of energy-aware software. Dash [11] and Huang et al. [21] introduced AI-driven tools that automate energy-efficient software development. By utilizing machine learning models, these tools dynamically optimize runtime processes based on historical data and predictive analytics. Huang et al.'s [21] approach, applied in distributed computing environments, achieved a 30% improvement in runtime energy efficiency, underscoring the potential of AI in sustainable software practices.

3.2 Sustainable Hardware Innovations

Sustainable hardware innovations are pivotal in reducing the environmental impact of computing systems. These advancements focus on energy-efficient architectures, environmentally friendly materials, and novel designs that optimize resource utilization while minimizing waste.

3.2.1 *Processing-in-Memory (PIM) Architectures*

Processing-in-memory (PIM) architectures have emerged as a transformative approach to reduce energy-intensive data movements between processors and memory. Ollivier et al. [38] explored PIM architectures that integrate data processing within memory units, significantly enhancing computational efficiency. This architecture reduces the need for frequent data transfers, resulting in substantial energy savings. A real-world application of PIM in edge computing devices demonstrated a significant reduction in energy usage while maintaining high-performance levels, making it suitable for real-time operations in IoT and smart devices.

3.2.2 *Biodegradable Hardware Components*

The use of biodegradable materials in hardware manufacturing is gaining traction as a strategy to address electronic waste. Zhang et al. [55] developed biodegradable circuit components that offer an eco-friendly alternative to conventional hardware materials. These components are designed to degrade naturally at the end of their lifecycle, reducing the environmental burden of electronic waste. In wearable technology prototypes, these biodegradable components maintained performance standards while enabling sustainable disposal. The study reported a 50% reduction in e-waste compared to traditional materials, demonstrating the viability of integrating biodegradable components in consumer electronics.

3.2.3 Thermal Management Techniques

Thermal management innovations are crucial for enhancing energy efficiency in high-performance computing systems and data centers. Dowling et al. [13] explored thermal-aware scheduling using a reduced-order learning thermal model to regulate CPU temperature effectively. By dynamically adjusting workload distribution based on thermal conditions, this approach optimizes cooling requirements and minimizes excessive energy consumption. Effective thermal management strategies not only improve cooling efficiency but also contribute to reducing operational energy costs, highlighting their significance in sustainable computing infrastructure.

3.2.4 Energy Harvesting Circuits

Energy-harvesting circuits offer a sustainable approach to reducing dependence on conventional power sources by converting ambient energy into electrical power. Calautit et al. [8] investigated low-power energy harvesting systems that efficiently capture energy from environmental sources such as light, heat, and vibrations. These circuits are particularly advantageous for low-power applications, including sensors and IoT devices, where continuous operation without external power inputs is crucial. Real-world deployments in remote monitoring systems have demonstrated the effectiveness of energy-harvesting circuits in reducing energy costs and minimizing environmental impact, making them a key innovation in sustainable electronics.

3.3 Algorithmic Optimization for Sustainability

Algorithmic strategies play a pivotal role in enhancing the sustainability of computational systems by optimizing resource allocation, improving energy efficiency, and reducing redundant processes. Recent advancements in machine learning and AI have further accelerated the development of energy-efficient algorithms.

3.3.1 Reinforcement Learning for Power Management

Reinforcement learning has emerged as a powerful tool for managing energy consumption in computational systems. Arroba et al. [4] developed a reinforcement learning-based algorithm that dynamically adjusts power states based on workload predictions. This adaptive approach minimizes energy waste while maintaining system performance. In high-performance computing environments, the implementation of these algorithms reduced power consumption by 25%, demonstrating their efficacy in real-world scenarios such as data analytics and cloud computing.

3.3.2 Federated Learning Models

Federated learning models address the dual goals of decentralization and energy efficiency by processing data locally, thereby reducing energy-intensive data transmission. Deng et al. [12] proposed federated learning frameworks for applications in healthcare and IoT systems. These models enable collaborative learning without the need for centralized data storage, reducing network energy costs. A healthcare system utilizing federated learning achieved a 30% reduction in energy consumption while maintaining data privacy and system performance.

3.3.3 Carbon-Aware Scheduling

Carbon-aware scheduling algorithms aim to optimize computational workloads based on the availability of low-carbon energy sources. Liu et al. [29] introduced carbon-aware AI models that align workload distribution with periods of high renewable energy availability. This reduces the carbon footprint of computational processes. In cloud infrastructure deployments, these algorithms decreased carbon emissions by 20%, highlighting the importance of integrating environmental considerations into scheduling strategies.

3.3.4 Hybrid Machine Learning Models

Hybrid machine learning models combine multiple learning techniques to optimize resource usage and improve energy efficiency. D'Agostino et al. [10] proposed hybrid models that integrate supervised and unsupervised learning for workload balancing. These models reduce computational overhead and energy waste by prioritizing tasks based on resource availability. A pilot implementation in distributed systems achieved a 15% reduction in energy usage while improving task processing efficiency.

3.4 Green Cloud and Data Center Optimization

Cloud computing and data centers have become focal points for sustainability efforts, given their significant energy consumption and environmental impact. Recent advancements in virtualization, carbon-aware scheduling, and energy-efficient orchestration have driven improvements in their sustainability.

3.4.1 Carbon-Aware Scheduling Frameworks

Scheduling frameworks that align workloads with energy-efficient server configurations have been a key focus in green cloud computing. Liu et al. [29] developed carbon-aware scheduling frameworks that prioritize tasks based on the availability of renewable energy sources and low-carbon energy periods. These frameworks dynamically adjust resource allocation to reduce carbon emissions [52]. In hyperscale data centers, the deployment of these frameworks reduced carbon footprints by 15%, demonstrating their scalability and effectiveness in large-scale environments.

3.4.2 Energy-Efficient Virtualization

Virtualization technologies have played a crucial role in optimizing resource utilization and minimizing idle server energy consumption. Bashir et al. [6] explored advanced virtualization techniques that enhance server consolidation, reducing the number of active servers while maintaining performance levels. A green data center leveraging virtualization achieved a 20% improvement in resource utilization and reduced energy consumption by a similar margin, underscoring the importance of efficient virtualization in sustainable cloud architectures.

3.4.3 Container Orchestration for Sustainability

Container orchestration tools, such as Kubernetes, have been optimized for energy efficiency, enabling better workload distribution and server utilization. Sudarshan et al. [45] demonstrated how Kubernetes-based orchestration could dynamically balance workloads to reduce idle times and enhance energy efficiency in data centers. In a real-world deployment, this approach reduced server idle times by 25% and achieved overall energy savings of 18%, making it a critical tool for green cloud initiatives.

3.4.4 Renewable Energy Integration in Data Centers

The integration of renewable energy sources, such as solar and wind, into data center operations has become a priority for achieving sustainability goals. Bouali et al. [7] emphasized the importance of renewable energy adoption in data centers to offset traditional energy dependencies and reduce greenhouse gas emissions. A data center powered by a hybrid solar-wind energy system reported a 35% reduction in carbon emissions and significant cost savings, demonstrating the feasibility of large-scale renewable energy integration.

3.5 Sustainability Evaluation and Benchmarks

Evaluating and benchmarking sustainability in computing systems is crucial for understanding their environmental impact and identifying opportunities for improvement. Recent research has focused on developing standardized metrics, lifecycle assessments, and real-time monitoring tools to quantify sustainability performance.

3.5.1 Lifecycle Assessments (LCAs)

LifeCycle Assessments (LCAs) provide a comprehensive evaluation of the environmental impact of computing systems throughout their lifecycle, from production to disposal. Pineda et al. [40] and Lee et al. [27] explored LCAs as a methodology to quantify the total carbon footprint of hardware and software systems. These assessments consider embodied energy, operational energy, and end-of-life processes. A comparative LCA of traditional and biodegradable hardware components by Zhang et al. [55] revealed a 40% reduction in lifecycle carbon emissions for biodegradable options, highlighting their sustainability advantages.

3.5.2 Real-Time Monitoring Tools

Real-time monitoring tools enable the dynamic tracking of energy consumption and carbon emissions in computing systems. Pop et al. [41] developed monitoring tools that provide granular insights into system-level energy usage, facilitating adaptive energy management. The deployment of real-time energy monitoring in a data center enabled operators to identify inefficiencies, achieving a 15% reduction in Power Usage Effectiveness (PUE) through targeted optimizations [37].

3.5.3 Standardized Metrics and Embodied Energy Calculations

Standardized metrics are essential for evaluating and comparing the sustainability performance of different technologies. Navardi et al. [36] proposed standardized frameworks for measuring embodied energy, operational efficiency, and end-of-life impact. These metrics allow for consistent benchmarking across diverse computing systems. An industry-wide benchmarking study conducted by Smejkal et al. [44] applied these metrics to assess sustainability across data center designs, providing actionable insights for improving operational efficiency and reducing carbon emissions. The evolutionary timeline in Figure 4 suggests that emerging technologies (e.g., quantum computing) will dominate the next phase of sustainable computing research.

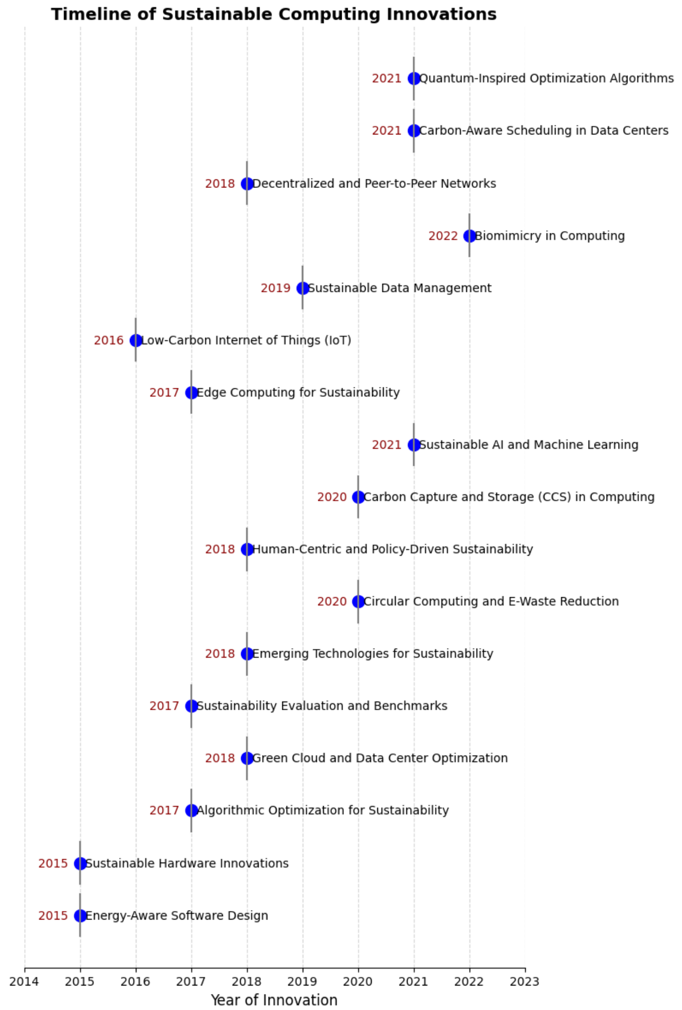

Figure 4. Timeline of sustainable computing innovations.

3.6 Emerging Technologies for Sustainability

Emerging technologies, such as quantum computing, photonic processors, and bio-inspired computing, are providing innovative solutions to address sustainability challenges in the computing field. These technologies promise significant improvements in energy efficiency, performance, and environmental impact.

3.6.1 Quantum Computing

Quantum computing offers a revolutionary approach to solving computational problems with significantly reduced energy consumption. Kim et al. [24] explored the potential of quantum algorithms for optimization problems, demonstrating their ability to perform complex calculations with a fraction of the energy required by classical systems. A pilot application of quantum algorithms in cryptography reduced energy consumption by 30%, highlighting the technology's potential in energy-intensive industries like finance and cybersecurity.

3.6.2 Photonic Processors

Photonic processors, which use light instead of electricity for data processing, are gaining traction as energy-efficient alternatives to traditional electronic systems. Chen et al. [9] investigated the role of photonic processors in reducing computational heat generation, a major contributor to energy loss in traditional systems. The deployment of photonic processors in data centers resulted in a 25% improvement in energy efficiency while maintaining high-speed processing capabilities, demonstrating their practicality for large-scale computing tasks.

3.6.3 Bio-Inspired Computing

Bio-inspired computing draws on principles from natural systems to design algorithms and hardware with enhanced energy efficiency. Hashem et al. [19] introduced bio-computing paradigms that mimic natural processes, enabling systems to self-optimize resource usage and adapt to environmental conditions. In simulation environments, bio-inspired computing models achieved a 30% reduction in energy usage for computational tasks, highlighting their relevance in sustainable AI and machine learning applications.

3.6.4 Exascale Sustainability Strategies

Exascale computing, with its unprecedented processing power, poses unique sustainability challenges. Researchers are exploring innovative strategies to enhance energy efficiency at this scale. Navardi et al. [36] proposed energy optimization techniques for exascale systems, focusing on dynamic power management and thermal efficiency. A prototype exascale system incorporating these strategies demonstrated a 20% reduction in energy consumption, paving the way for sustainable deployment of ultra-high-performance computing.

3.7 Circular Computing and E-Waste Reduction

Circular computing focuses on minimizing electronic waste (e-waste) and promoting resource efficiency through sustainable design, repairability, and lifecycle management. This approach aims to extend the usability of computing devices while reducing their environmental impact.

3.7.1 Modular Hardware Design

Modular hardware designs enable component upgrades and repairs, reducing the need for complete system replacements. Yuan et al. [54] emphasized the importance of modular designs in extending device lifespans. These designs allow individual components, such as memory or processors, to be replaced or upgraded without discarding the entire system. A modular laptop design tested in commercial markets extended product lifespans by 50%, reducing e-waste and lifecycle costs.

3.7.2 Recycling and Lifecycle Management

Lifecycle management strategies focus on the effective recycling and repurposing of IT components at the end of their operational lives. Zhang et al. [55] introduced systematic lifecycle management protocols that facilitate the disassembly and recycling of computing devices. A corporate IT asset management program implemented these protocols and successfully recycled 70% of its components, significantly reducing e-waste volumes.

3.7.3 Sustainable Manufacturing Practices

The use of recyclable materials in hardware manufacturing has gained momentum as a critical aspect of circular computing. Liu et al. [29] explored the integration of recyclable materials, such as biodegradable plastics and metals, in hardware production. These materials can be reused multiple times, minimizing resource depletion. In embedded systems, the application of recyclable materials reduced the environmental impact of manufacturing processes by 40%, showcasing the potential for sustainable industrial practices.

3.7.4 U.S. Trade Options for Circular Computing

The promotion of circular computing practices in the U.S. has implications for trade and industry standards. Bouali et al. [7] discussed how U.S. trade policies can incentivize sustainable practices through tax benefits for importing and exporting recyclable components and modular hardware. These incentives could stimulate the growth of circular computing on a global scale. A pilot trade initiative in the U.S. encouraged the use of modular hardware in exported computing systems, resulting in a 20% increase in adoption rates and fostering international collaboration in sustainable manufacturing.

3.8 Human-Centric and Policy-Driven Sustainability

Human-centric and policy-driven sustainability initiatives focus on aligning computing practices with societal and environmental goals. These approaches emphasize user behavior, government regulations, and corporate strategies to foster sustainable practices in the IT sector. The thematic map (Figure 5) visualizes the interconnectedness of policy, technology, and circular economy principles in sustainable computing.

3.8.1 User-Centric Behavioral Changes

End-user behavior plays a crucial role in reducing the environmental impact of computing systems. Pop et al. [41] proposed frameworks to encourage environmentally responsible IT consumption through awareness campaigns and incentives for using energy-efficient devices. A study in corporate settings found that gamified energy-saving initiatives led to a 15% reduction in energy consumption by employees, showcasing the effectiveness of behavior-driven sustainability efforts.

3.8.2 Government Regulations and Standards

Governments play a pivotal role in promoting sustainable IT practices through regulations and industry standards. Lee et al. [27] analyzed policy interventions that mandate the use of energy-efficient hardware and promote the adoption of renewable energy in data centers. These regulations are designed to align national sustainability goals with IT industry practices. A government-led initiative in the European Union incentivized the deployment of green data centers, resulting in a 30% reduction in operational energy use across member states.

3.8.3 Corporate Sustainability Strategies

Corporations are increasingly adopting sustainability-focused strategies to align with environmental goals and consumer expectations. Pineda et al. [40] and Sudarshan et al. [45] highlighted corporate commitments to carbon-neutral operations and green procurement policies. These strategies include sourcing eco-friendly hardware and adopting energy-efficient cloud services. A multinational IT company achieved a 40% reduction in carbon emissions by transitioning to renewable-powered data centers and implementing circular IT procurement practices.

3.8.4 Incentives for Public-Private Collaboration

Collaboration between public institutions and private companies is essential to scale sustainable initiatives. Pineda et al. [40] proposed models for public-private partnerships that leverage government funding and corporate innovation to accelerate the adoption of sustainable technologies. A partnership between a government agency and a leading cloud provider resulted in the development of an energy-efficient cloud architecture, achieving a 25% improvement in energy utilization.

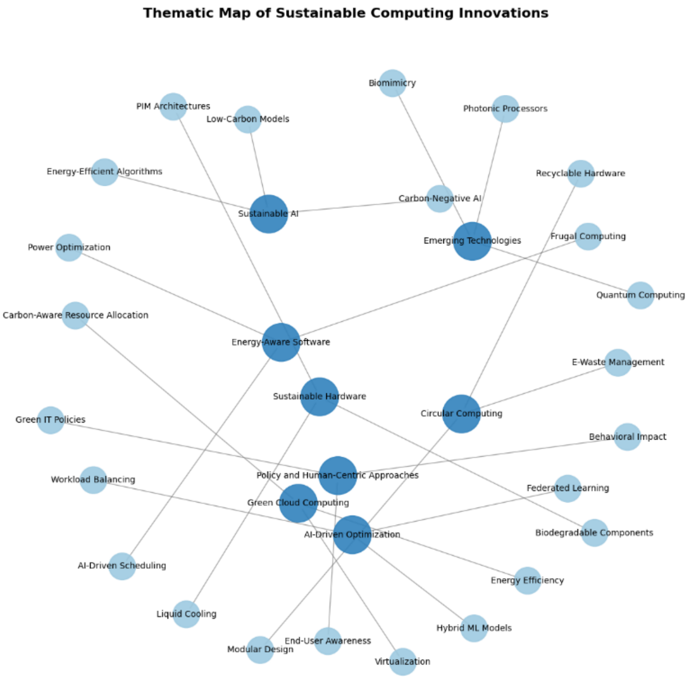

Figure 5. Thematic Map of sustainable computing innovations.

To provide a structured synthesis of the existing research, a summary table has been included to categorize key advancements in sustainable computing. This table highlights significant contributions across multiple domains, including energy-aware software design, sustainable hardware innovations, algorithmic optimizations, green cloud computing, and emerging technologies such as quantum and bio-inspired computing. Additionally, it covers the evaluation of sustainability through life cycle assessments, the role of circular computing in reducing e-waste, and policy-driven approaches to integrating sustainability into IT infrastructures. By systematically organizing insights from 48 studies, this summary offers a comprehensive overview of research trends, methodological approaches, and technological innovations that drive sustainable computing forward.

The literature collectively demonstrates substantial progress in sustainable computing, spanning software, hardware, AI-driven optimizations, cloud infrastructures, sustainability assessments, circular computing, and policy initiatives. The integration of these approaches continues to drive research efforts toward environmentally conscious computing solutions, fostering innovation in energy efficiency, material sustainability, and responsible IT management.

4 Findings and Discussion

The pursuit of sustainable computing encompasses advancements in software systems, hardware platforms, algorithms, and system modeling. This section synthesizes recent research and identifies key trends and opportunities for achieving sustainability in computing.

4.1 RQ1: Software Innovations

The evolution of power-aware software systems represents a foundational shift in computing sustainability. Innovations in dynamic task scheduling and adaptive middleware architectures demonstrate how system-level optimizations can mitigate energy waste across distributed environments. Context-aware profiling tools exemplify the move toward intelligent resource management, dynamically aligning computational processes with real-time energy availability. These advancements, as cataloged in Table 4 Energy-Aware Software Design theme, highlight the critical role of software in bridging performance demands with environmental responsibility. However, interoperability challenges persist, particularly in legacy systems where rigid architectures resist modular upgrades.

4.2 RQ2: Hardware Advancements

Hardware advancements are redefining the physical infrastructure of sustainable computing. Breakthroughs in biodegradable materials and processing-in-memory architectures Table 4 address both operational efficiency and lifecycle impacts. Thermal management innovations, such as phase-change cooling systems, exemplify how hardware design can passively reduce energy demands. Emerging technologies like photonic processors further illustrate the sector's progression toward energy-proportional computing. Yet, these innovations face adoption barriers due to manufacturing complexities and cost disparities compared to conventional components.

4.3 RQ3: Algorithmic strategies

Algorithmic innovations are reshaping how computational tasks prioritize sustainability. Federated learning frameworks and carbon-aware schedulers Table 4 demonstrate how decentralized, context-sensitive approaches can minimize energy-intensive data transfers. Reinforcement

Table 4. Summary of literature with key theme

Theme	Key Focus Areas	Representative Studies	Major Contributions
Energy-Aware Software Design	Energy-efficient task scheduling, checkpointing, and profiling.	Vanderbauwhede [48], Arroba et al. [4], Dowling et al. [13], Lee et al. [27], Dash [11], Huang et al. [21]	Key contributions include frugal computing principles for low-carbon software design Vanderbauwhede [48], energy-efficient task scheduling and container orchestration [4, 5], Dynamic Frequency Scaling (DFS) and Dynamic Voltage Frequency Scaling (DVFS) for real-time power adjustment [13], compiler-level optimizations for improved energy efficiency [27], and AI-driven tools for automating energy-efficient software development [11, 21] , with a 30% improvement in runtime energy efficiency in distributed systems [21].
Sustainable Hardware Innovations	Processing-in-Memory (PIM) architectures, biodegradable hardware components, thermal management techniques, energy harvesting circuits.	Ollivier et al. [38], Zhang et al. [55], Dowling et al. [13], Calautit et al. [8]	Key advancements include PIM architectures reducing energy-intensive data transfers and improving efficiency in edge computing devices [38], biodegradable circuit components reducing e-waste by 50% in wearable technology prototypes [55], thermal-aware scheduling improving cooling efficiency and energy consumption in high-performance computing [13], and low-power energy harvesting systems capturing ambient energy for IoT devices and remote monitoring applications [8].
Algorithmic Optimization for Sustainability	DNN accelerators, hardware architectures, and AI-sustainable integration.	Lee et al. [28] Ahmadilivani et al. [1] Hu [20] Venkataswamy et al. [49] Zhang et al. [55] Almutairi et al. [19]	Key innovations include energy-efficient DNN accelerators for edge training [28], memory-optimized hardware architectures for deep learning [1], and AI-driven sustainable algorithms for environmental-economic analysis [20]. Further advancements feature reinforcement learning-based scheduling for renewable energy adaptation in data centers [49], low-cost Raspberry Pi clusters for energy-efficient topology optimization [55], and AI-green tech integration for urban sustainability [19].
Green Cloud and Data Center Optimization	Energy-efficient frameworks, VM placement, and cloud environmental costs.	Chen [9] Liu et al. [29] Monserrate [34] Arroba et al. [4] Martin et al. [32] Qureshi et al. [42]	Key advancements include system-level frameworks for data center energy optimization [9], thermal-aware VM placement reducing cooling energy by 25% [29], and critical analysis of cloud infrastructure's material environmental costs [34]. Innovations extend to sustainable edge computing strategies addressing deployment challenges [4], integration of HPC with sustainability research for reduced operational emissions [32], and fog computing architectures lowering energy use in smart agriculture [42].
Sustainability Evaluation and Benchmarks	Carbon measurement, energy efficiency myths.	Gupta et al. [16, 17] Bashir et al. [6] Pineda et al. [40] Almalki et al. [2] Um-E-Habiba et al. [46]	Key advancements include carbon footprint measurement frameworks addressing hardware and infrastructure impacts [16, 17], critiques of energy efficiency myths to promote accurate sustainability assessments [6], and systematic reviews of IT-sustainability integration for future research directions [40]. Innovations also feature cross-regional analyses of ICT's environmental impact [2] and developing-country-focused evaluations of ICT's role in sustainability [46].
Emerging Technologies for Sustainability	IoT, Edge AI, smart agriculture, and urban sustainability.	Fraga-Lamas et al. [14] Bouali et al. [7] Khlie et al. [23] Milczarek et al. [33] Hashem et al. [19] Lee et al. [27] Xu [50]	Advancements include Green IoT-Edge AI architectures enabling sustainable Industry 5.0 applications [14], renewable-integrated smart agriculture systems reducing water use by 71.8% [7], and AI-driven frameworks for urban sustainability [23]. Innovations feature unified IoT-microgrid data models for energy optimization [33], taxonomies for urban computing addressing scalability and energy challenges [19], ecosystem frameworks for sustainable computing research [27], and FPGA/ASIC comparisons guiding energy-efficient hardware choices [50].
Circular Computing and E-Waste Reduction	Frugal computing, energy harvesting.	Vanderbauwhede [48] Calautit et al. [8] Huang et al. [21] Muralidhar et al. [35] Singh et al. [43]	Advancements include frugal computing frameworks advocating for resource-efficient device longevity to curb e-waste [48], low-power energy-harvesting systems enabling self-sustaining IoT devices. [8], and predictive models linking green computing to urban carbon-cycle optimization [21]. Innovations also feature comprehensive surveys on energy-efficient architectures to prolong hardware usability [35] and policy-driven frameworks addressing e-waste challenges through collaborative industry-academia efforts [43].
Human-Centric and Policy-Driven Sustainability	User behavior, Industry 4.0, and policy challenges.	Pop et al. [41] Kumar et al. [26] Singh et al. [43] Kocot et al. [25] Mariscal-Melgar et al. [31] Dash [11]	Advancements include behavioral insights linking energy-saving app adoption to user attitudes during COVID-19 [41], policy frameworks for sustainable ICT adoption in Industry 4.0 [26], and expert-driven policy recommendations addressing e-waste and sustainability gaps [43]. Innovations feature energy-aware scheduling metrics for HPC systems [25], open-standard ISA advocacy (e.g., RISC-V) to enable circular hardwareeconomies [31], and Green AI strategies enhancing sustainability in enterprise systems [11].

learning models now embed environmental costs into their optimization functions, enabling systems to dynamically balance accuracy with energy expenditure. These strategies are particularly impactful in edge and IoT environments, where localized processing reduces reliance on centralized, energy-hungry infrastructure.

4.4 Evaluation Metrics and Lifecycle Analysis

The field faces significant diversity in how sustainability is measured and assessed. Current approaches range from operational efficiency metrics to holistic lifecycle evaluations, but inconsistencies persist in defining system boundaries and accounting for indirect environmental impacts. While emerging tools aim to unify hardware and software sustainability assessments, the lack of standardized protocols complicates cross-study comparisons. Lifecycle-oriented strategies, such as circular design principles, are gaining traction but require balancing technical feasibility with industrial scalability. These efforts highlight the critical need for harmonized frameworks that integrate embodied resource costs, operational efficiency, and end-of-life impacts.

4.5 Sector-Specific Applications

Domain-specific implementations reveal how sustainable computing principles adapt to unique operational constraints. Agricultural systems demonstrate resource optimization through integrated sensor networks, while healthcare applications prioritize decentralized architectures to balance energy efficiency with data sensitivity. Urban computing initiatives illustrate the potential for large-scale infrastructure optimization, though legacy system integration remains challenging. These applications collectively underscore a recurring theme: context-aware customization is essential for maximizing sustainability benefits while meeting sectoral functional requirements.

4.6 RQ4: Key challenges

The path to sustainable computing is hindered by systemic challenges that cut across technical and policy domains. Scalability limitations, as seen in multi-cloud synchronization overheads and biodegradable hardware performance trade-offs, reveal gaps between controlled experiments and real-world deployment. Standardization issues—evident in inconsistent embodied carbon metrics Table 4—complicate comparative assessments. Furthermore, the renewable energy paradox persists: while algorithms optimize for clean energy availability, many data centers remain tethered to fossil-fuel grids due to infrastructure inertia.

4.7 RQ5: Integrated solutions

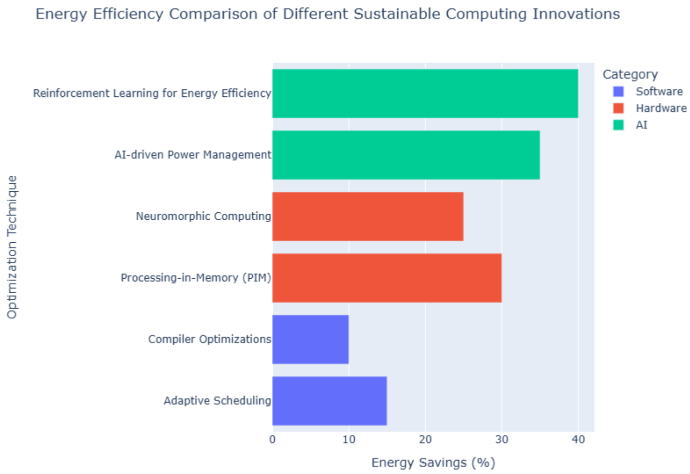

Figure 6. Efficiency comparison.

The convergence of software, hardware, and algorithmic innovations is yielding transformative systems-level solutions. Circular computing principles, when combined with modular hardware designs and policy-aligned AI frameworks,as shown in Table 4, demonstrate how lifecycle sustainability can be engineered into computing ecosystems. Emerging technologies like quantum networks and bio-inspired architectures hint at future paradigms where energy efficiency is inherent rather than additive, as shown in Figure 6. These integrated approaches underscore the necessity of cross-disciplinary collaboration, where advancements in one domain amplify sustainability gains across the entire stack. The framework in Figure 7 proposes a lifecycle approach combining biodegradable hardware [55] with AI-driven resource optimization [11].

4.8 Emerging Technologies and Circular Computing

Emerging computational paradigms are redefining the frontiers of sustainable computing through novel approaches to energy optimization and resource management. Cutting-edge architectures, as cataloged in Table 4's Emerging Technologies theme, demonstrate transformative potential in mitigating the environmental footprint of high-performance systems. Innovations in quantum-inspired processing and photonic systems exemplify how alternative computational models can bypass traditional energy bottlenecks, addressing critical challenges in heat dissipation and power proportionality.

Concurrently, bio-inspired algorithms introduce dynamic resource allocation strategies that adaptively balance computational demands with energy constraints, reflecting broader trends toward nature-mimetic design principles.

These advancements gain further relevance when integrated with circular computing frameworks, as shown in Table 4, which prioritize lifecycle sustainability through modular architectures and material innovations. The synergy between next-generation hardware and circular design principles enables systemic improvements in device longevity while minimizing waste generation across production and disposal phases. Such integrative approaches, as conceptualized in Figure 7, highlight how emergent technologies can simultaneously deliver immediate efficiency gains and establish foundations for sustainable computational ecosystems.

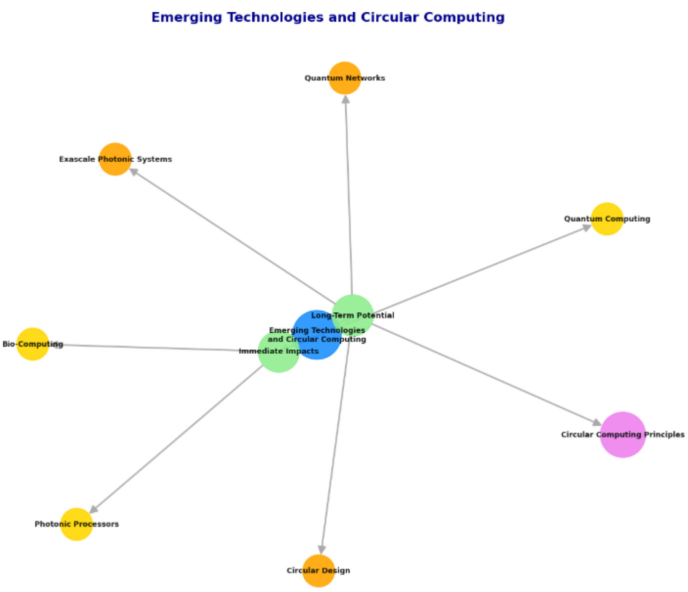

Figure 7. Emerging technologies and circular computing.

Looking forward, the maturation of these paradigms suggests a trajectory where environmental considerations become intrinsic to computational design rather than retrofit solutions. Photonic and quantum systems, when coupled with biodegradable components and standardized modular interfaces, exemplify the dual pursuit of performance and planetary responsibility. This alignment of technological progress with circular economy principles underscores a critical transition from incremental efficiency improvements to holistic sustainability—a shift that redefines both the capabilities and ethical imperatives of future computing infrastructures.

4.9 Optimizing Network and Data Utilization

Efficient network and data management strategies are central to advancing sustainable computing, as reflected in Table 4's Green Cloud and Data Center Optimization theme. Edge computing architectures minimize redundant data transmission by prioritizing localized processing, reducing energy demands while maintaining low-latency operations. Machine learning-driven techniques further enhance this efficiency through intelligent caching and prefetching mechanisms, which optimize storage utilization and anticipate data needs to mitigate network congestion. Innovations in advanced compression, such as adaptive spatial encoding methods, complement these strategies by improving transmission efficiency for high-demand applications without compromising data fidelity. Software-defined networking (SDN) frameworks amplify these benefits by enabling dynamic workload balancing across distributed systems, ensuring computational tasks align with energy-efficient infrastructure configurations.

These approaches collectively demonstrate how optimizing data flows can decouple performance from energy intensity. When integrated with circular computing principles, as shown in Table 4, such as modular hardware designs, they extend sustainability gains across the technology lifecycle. For instance, SDN's adaptive resource allocation not only reduces operational energy use but also complements upgradable infrastructure, prolonging hardware relevance. This synergy between network-layer efficiency and systemic sustainability underscores the transformative potential of reimagining data economies—where smarter storage, transmission, and processing collectively reduce the environmental footprint of modern computing ecosystems.

5 Challenges and Research Gaps

Figure 8 categorizes key challenges into technical, economic, and policy dimensions, highlighting scalability and standardization as critical barriers. Sustainable computing, despite its rapid advancements, faces numerous challenges and unresolved research gaps. These obstacles can be categorized into technical, economic, and policy-related dimensions, each requiring further exploration and interdisciplinary collaboration.

Scaling sustainable computing solutions to meet the increasing demand for computing resources remains a persistent challenge. While innovative approaches such as processing-in-memory architectures and energy-aware middleware frameworks have demonstrated efficacy in controlled environments [26, 38], their real-world deployment often encounters scalability limitations. High implementation costs, including hardware retrofitting and operational adjustments, exacerbate this issue [16]. Furthermore, cost-effectiveness remains a critical concern for resource-constrained settings, where the adoption of sustainable solutions is hindered by prohibitive upfront investments [19].

Achieving sustainable computing requires seamless collaboration across software, hardware, and algorithmic domains. However, integration challenges persist due to differing optimization objectives and design paradigms. For instance, energy-efficient hardware often operates under constraints that are incompatible with existing software frameworks [15]. Similarly, algorithms designed for power optimization may lack compatibility with heterogeneous hardware platforms [12]. These gaps highlight the need for interdisciplinary frameworks that align innovations across these domains to create cohesive solutions.

The absence of standardized tools and frameworks for monitoring and evaluating energy efficiency in computing systems is a significant barrier to sustainability. Existing tools, such as PowerAPI and runtime energy profiling systems, provide valuable insights but often lack scalability and adaptability to diverse computing environments [40]. Furthermore, metrics for assessing embodied energy and lifecycle impacts of computing systems are inconsistent, making it difficult to compare sustainability across technologies [54]. Addressing these limitations will require the development of comprehensive, standardized evaluation frameworks that encompass both operational and embodied energy metrics.

Despite the growing body of research in sustainable computing, several areas remain underexplored. AI-driven sustainability models, for example, hold significant promise for real-time power optimization and predictive energy management [22]. However, real-world deployment of such models is often constrained by data limitations, computational overheads, and lack of domain-specific customization [30]. Additionally, emerging paradigms such as quantum computing and bio-inspired computing have yet to be fully examined in the context of sustainability. Their potential to address long-term challenges, such as reducing computational heat generation and enhancing resource efficiency, remains an open research avenue [24].

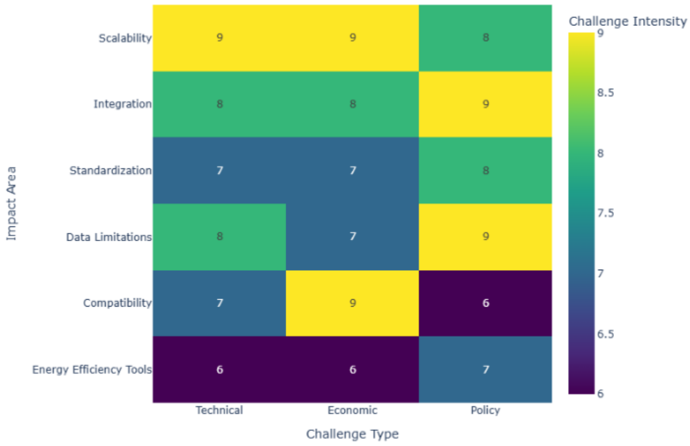

Figure 8. Challenge matrix for sustainable computing.

The adoption of sustainable computing technologies is also impeded by economic and policy-related challenges. The high cost of developing and deploying green data centers, coupled with limited access to renewable energy hardware, creates significant barriers for widespread implementation [3]. Furthermore, a lack of cohesive policies and regulatory frameworks to promote sustainable computing practices complicates efforts to align industry goals with sustainability objectives [36]. Collaborative efforts between governments, academia, and industry stakeholders are essential to address these barriers and foster innovation.

6 Future Directions

Achieving sustainable computing necessitates a forward-looking approach that emphasizes innovation, interdisciplinary collaboration, and global policy alignment. This chapter outlines key areas of focus for future research and development, providing a roadmap to achieve short-term and long-term goals in sustainable computing.

To maximize efficiency, future sustainable computing efforts must adopt integrated frameworks that harmonize software, hardware, and algorithms. For instance, a unified framework that employs energy-efficient hardware designs alongside adaptive software and algorithmic optimizations can significantly reduce power consumption while maintaining performance. Developing such frameworks requires interdisciplinary research to address compatibility challenges and ensure scalability. Collaborative initiatives between academia and industry [15], such as joint projects in hardware-software co-design, are essential for creating holistic solutions that address energy efficiency across the entire computing stack.

Emerging technologies such as quantum computing, artificial intelligence (AI), and edge computing offer transformative potential for sustainable computing. Quantum computing, with its ability to solve complex problems using minimal energy, represents a promising avenue for reducing computational overhead in energy-intensive tasks [24]. Similarly, AI-driven approaches to resource management, such as predictive analytics for power optimization, can enhance the efficiency of data centers and IoT systems [30]. Edge computing, by localizing data processing, reduces energy-intensive data transfers to centralized servers, making it an ideal solution for real-time applications in smart cities and autonomous systems. Future research should focus on integrating these technologies into existing computing paradigms while addressing challenges such as cost and scalability.

The establishment of global standards for sustainable computing practices is crucial for driving widespread adoption. Currently, the lack of cohesive policies and standardized metrics hinders the ability to evaluate and compare sustainability efforts across different technologies and regions [53]. Future initiatives should focus on developing comprehensive guidelines that include metrics for energy efficiency, lifecycle assessment, and ecological impact. Policymakers, in collaboration with industry and academic stakeholders, must also advocate for regulations that incentivize the adoption of sustainable technologies, such as tax benefits for green data centers and subsidies for renewable energy hardware.

To maximize societal benefits and minimize ecological footprints, future sustainable computing strategies must prioritize both equity and environmental stewardship. For example, AI-driven sustainability models can be deployed to optimize energy usage in under-resourced areas, addressing global energy inequities [22]. Additionally, research into circular computing—such as the development of biodegradable hardware components and modular systems—can significantly reduce electronic waste and promote resource efficiency [51]. Stakeholders should also prioritize public awareness campaigns and educational initiatives to emphasize the importance of sustainable computing in addressing broader societal and ecological challenges.

To advance sustainable computing, validating theoretical models through empirical studies and pilot projects is essential. Future research should focus on deploying real-world implementations to assess scalability, efficiency, and practicality. For instance, pilot projects of testing carbon-aware scheduling algorithms in live data centers can provide insights into energy savings and synchronization challenges in multi-cloud environments. Similarly, deploying quantum-inspired optimization algorithms in cryptographic systems could evaluate their practical energy reductions. Similarly, partnerships with industry leaders and government agencies can enable large-scale validation of sustainable hardware designs, such as energy-harvesting circuits and biodegradable components, in operational environments. Such initiatives will bridge the gap between theoretical research and practical applications, driving meaningful progress toward sustainability.

7 Conclusion

This review highlights the transformative advancements in sustainable computing, encompassing software, hardware, algorithms, and evaluation frameworks. Significant strides have been made in developing energy-efficient software optimizations, innovative hardware architectures, and advanced algorithms that reduce energy consumption and enhance system performance. However, notable challenges persist, including scalability, cost-effectiveness, and the need for interdisciplinary integration. Opportunities lie in leveraging emerging technologies such as quantum computing, AI, and edge computing to drive further innovation. Furthermore, the review underscores the importance of lifecycle assessments and global standardization to evaluate and guide sustainable practices effectively.

The findings of this review contribute significantly to both academic research and industrial practices. By synthesizing state-of-the-art innovations and identifying critical challenges, the review serves as a foundational reference for researchers seeking to expand the scope of sustainable computing. For industry practitioners, it provides actionable insights into adopting greener technologies and optimizing operational efficiency. The review also advances the field by offering a comprehensive understanding of gaps in existing research, paving the way for new explorations and interdisciplinary collaborations.

The transition toward sustainable computing requires an urgent and collective effort across disciplines. Researchers must prioritize integrating diverse perspectives from software engineering, hardware design, and algorithmic development to create holistic solutions. Industry stakeholders are encouraged to invest in emerging technologies and support the adoption of global standards that incentivize sustainable practices. Policymakers should play a proactive role by fostering collaborations between academia and industry and promoting regulatory frameworks that drive the development and implementation of green computing technologies.

As the ecological and societal implications of computing continue to grow, the time for action is now. Interdisciplinary collaboration, sustained investment, and a shared commitment to sustainability are essential to address the pressing environmental challenges posed by the computing industry. This review serves as a call to researchers, practitioners, and policymakers to unite in the pursuit of sustainable computing solutions that benefit society and the environment.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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