GREENING DATA CENTERS: PRACTICES, GAPS AND RESEARCH AGENDA

1 INTRODUCTION

The global advance of digitalization, driven by cloud computing, big data, and artificial intelligence (AI), has increased the demand for data centers. These infrastructures, essential to the digital society, already consume about 3% of global electricity supply and are significant sources of greenhouse gas emissions (Wen et al., 2021).

The rapid expansion of AI is likely to intensify this trend. Estimates indicate that the energy use associated with this technology may double by 2026 and triple by 2030, reaching about 1.3% of global electricity consumption (Senyapar & Bayindir, 2025). This prospect raises concerns about environmental impacts and climate resilience in a context of pressure for energy efficiency and the transition to a low carbon economy.

In response, the concept of sustainability in data centers, also called green data centers, has gained prominence. It involves strategies that reduce the use of natural resources, improve operational efficiency, and mitigate carbon footprints, consistent with circular economy (CE) principles (Elavarasi et al., 2025). Although research on sustainable data centers has progressed, comparative syntheses that systematize initiatives, identify patterns, and gaps remain scarce.

This article investigates the state of the art in sustainability practices for data centers through a systematic literature review. It maps the main strategies reported in the scientific literature and examines how they are discussed and assessed regarding energy efficiency, mitigation of CO_2 emissions, and alignment with broader sustainability principles.

Thus, the research questions (RQ) that guided this study are:

- RQ1: What sustainability practices have been discussed in the scientific literature on data centers?
- RQ2: What research gaps remain and what are the key avenues for advancing research and knowledge on green data centers?

By addressing these questions, the study advances the conceptual debate on data center sustainability and offers practical insights for decision makers seeking to foster greener digital infrastructures.

2 THEORETICAL BACKGROUND

The term green data center refers to facilities designed or adapted to reduce their environmental impact through energy efficiency, rational water use, and mitigation of greenhouse gas emissions. These centers adopt practices such as server virtualization, renewable energy integration, workload optimization, advanced cooling techniques, and heat recovery (Elavarasi et al., 2025). Metrics such as Power Usage Effectiveness (PUE) and Carbon Usage Effectiveness (CUE) are widely used to measure energy performance and carbon footprint, establishing benchmarks for the industry (Oró et al., 2015). The transition to green data centers is therefore considered fundamental to meeting digital demands in an environmentally responsible manner.

Cooling operations account for a significant share of the total energy consumption in data centers and are regarded as one of the main sources of environmental and economic impact in the sector (Yuan et al., 2025). The literature highlights the importance of solutions that reduce this intensity, including approaches based on higher operational efficiency and the use of intelligent monitoring techniques for continuous optimization. These initiatives have shown promising results in improving efficiency indicators and alleviating pressure on natural resources (Elavarasi et al., 2025).

In parallel, research also emphasizes the potential of strategies aligned with CE principles, in which flows traditionally considered waste can be transformed into useful resources for other sectors. A significant portion of the electricity used in data centers is dissipated as heat, which creates opportunities for integration projects with urban and industrial systems capable of reducing emissions and generating economic benefits (Hyvönen et al., 2024; Yuan et al., 2025).

The articulation of efficiency gains and by-product recovery demonstrates the strategic nature of sustainability in data centers. Beyond mitigating environmental impacts, these initiatives serve as vectors of innovation and contribute to energy and climate resilience on a global scale (Puentes Bejarano et al., 2024).

3 METHODOLOGY

3.1 SEARCH STRATEGY AND DATA BASES

This study is based on a systematic literature review conducted in accordance with the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) as proposed by Moher et al. (2009). The objective was to identify, select, and analyze studies addressing efficient cooling techniques and waste heat recovery strategies in the operational management of data centers. Searches were carried out in the Scopus and Web of Science (WoS) databases, which are widely recognized for their comprehensive coverage of scientific journals and academic rigor. The search strategy was initially structured for Scopus and subsequently adapted for WoS, as summarized in Table 1.

Tabela 1. Data bases and search strategies.

Data base	Search strategy
Scopus	TITLE-ABS-KEY (("Data Center" OR "Cloud Infrastructure") AND ("Energy Efficiency" OR "Renewable Energy" OR "Energy Management") AND ("Sustainability" OR "Environmental Impact" OR "Climate Change"))
Web of Science	TS = (("Data Center" OR "Cloud Infrastructure") AND ("Energy Efficiency" OR "Renewable Energy" OR "Energy Management") AND ("Sustainability" OR "Environmental Impact" OR "Climate Change"))

Source: Authors.

The searches were performed on August, 2025, and results were exported in BibTeX format. Duplicate records were identified and removed using Rayyan software, which eliminated 130 occurrences during the screening phase.

3.2 INCLUSION CRITERIA AND SCREENING PROCESS

Studies were included if they met the following conditions:

i. peer-reviewed journal articles ensuring reliability and methodological rigor;
ii. analysis of sustainability practices in data centers reporting energy efficiency gains and CO_2 emissions reduction;
iii. explicit presentation of results related to efficient cooling techniques and/or residual heat recovery.

The screening process involved two steps: first, the analysis of titles and abstracts; second, the full-text reading of preselected studies to extract relevant data. Extracted information included study objectives, methodological approach, type of technique addressed, proposed solutions, and main conclusions. The analysis was qualitative in nature, enabling thematic categorization of results and identification of patterns and research gaps. At the end of this process, 12 articles were selected to form the theoretical basis of this review.

3.3 DATA ANALYSIS AND SYSTEMATIZATION

After final selection and analysis of the references, results were organized and described using two main tools. Microsoft Excel was employed due to its accessibility and versatility in handling qualitative information. Python was also applied with the support of specialized libraries for analysis and visualization, including Streamlit, which enabled the development of interactive representations that supported data interpretation. The findings were systematized through spreadsheets and dashboards in both environments, providing a clear visualization of patterns, trends, and gaps in the literature. Based on these resources, the discussion emphasized the categorization of techniques and sustainability metrics applied to data centers.

4 RESULTS AND DISCUSSION

4.1 SUSTAINABLE PRACTICES FOR DATA CENTERS

To systematize the findings of the review, Table 2 summarizes the sustainable practices identified in the literature on data centers. For each practice, the table highlights the type of efficiency achieved and the corresponding reference, providing a consolidated view of the strategies currently shaping the debate on green data centers.

Tabela 2. Data bases and search strategies.

ID	Sustainable practice	Category	Efficiency	Reference
P1	Dielectric fluid cooling	Waste heat	Energy efficiency	Luo et al. (2019)
P2	Counterflow air duct system	Waste heat	Energy efficiency	Kargar et al. (2021)
P3	Immersion cooling integrated with biogas cells	Waste heat	CO_2 reduction	Bejarano et al. (2024)
P4	Data center with CCHP and residual heat reuse systems	Waste heat	Energy efficiency	Wan et al. (2020)
P5	Organic Rankine Cycle (ORC) driven by solar thermal energy	Waste heat	Energy efficiency	Liaqat et al. (2025)
P6	Heat recovery using absorption chiller (AC)	Waste heat	Energy efficiency and CO_2 reduction	Amiri et al. (2021)
P7	Hybrid Transformer-GRU architecture	Cooling	Energy efficiency	Ma et al. (2025)
P8	Solar absorption chiller	Cooling	Energy efficiency	González et al. (2025)
P9	Differential temperature control	Cooling	Energy efficiency	Zetten et al. (2025)
P10	Artificial neural network integration	Cooling	Energy efficiency	Varzaneh et al. (2025)
P11	Chiller with economizers	Cooling	Energy and water efficiency	Karimi et al. (2025)
P12	Free cooling system	Cooling	Energy efficiency	Gügül et al. (2023)

Source: Authors.

Table 2 illustrates the range of sustainability practices most frequently discussed in the literature, grouped into two main categories: waste heat recovery (P1-P6) and cooling optimization (P7-P12). A clear pattern emerges, with the majority of contributions focusing on technical solutions aimed at reducing energy intensity. Waste heat recovery practices are explored through different pathways, from thermodynamic cycles such as the Organic Rankine Cycle (P5) to integration with cogeneration systems (P4) and biogas cells (P3). Approaches such as dielectric fluid cooling (P1), counterflow air ducts (P2), and absorption chillers (P6) reinforce the recurring attempt to transform dissipated energy into valuable outputs, which reflects strong alignment with CE principles.

Cooling practices, by contrast, demonstrate a broader mix of incremental and advanced innovations. Incremental strategies include economizers (P11), solar absorption chillers (P8), and differential temperature control (P9), all of which present relatively low implementation barriers. Meanwhile, AI applications, such as neural networks (P10) and hybrid Transformer-GRU architectures (P7), illustrate a more disruptive direction, relying on digital tools to dynamically optimize cooling operations. The presence of free cooling solutions (P12) further underscores the importance of context-specific factors, as climate conditions directly influence their feasibility.

Although these practices contribute significantly to energy efficiency, the evidence also reveals important limitations. Only P11 explicitly addresses water efficiency, despite the high water demand of many cooling systems. Similarly, direct CO_2 reduction is emphasized mainly in P3 and P6, suggesting that carbon mitigation is often treated as a secondary outcome rather than a central goal.

4.2 ADVANCING RESEARCH ON GREEN DATA CENTERS: AN AGENDA

Table 3 shows promising avenues to advance research on green data centers.

Tabela 3. Research agenda for green data centers.

Themes	Key topics	Description	Suggestions
Integrated frameworks	Energy, cooling, circular practices	Studies focus on isolated solutions; integrated approaches are needed.	Develop and test frameworks in real-world data centers
Metrics	PUE, CUE, WUE, lifecycle impacts	Metrics remain energy-centered; wider sustainability indicators are missing.	Create and validate multi-criteria metrics and benchmarks
Governance and society	Policy, regulation, stakeholders	Technical focus prevails; governance and social aspects are underexplored.	Conduct cross-country policy studies and governance models.
Digital technologies	AI, digital twins	Emerging tools can optimize cooling, workloads, and maintenance.	Apply AI and digital twins to optimize multi-resource use.
CE beyond energy	Material reuse, modular design, urban symbiosis	Energy recovery dominates; material and lifecycle aspects are overlooked.	Investigate closed-loop IT cycles and urban integration projects

Source: Authors.

Table 3 highlights that research on green data centers remains fragmented, concentrated on efficiency-oriented solutions, while systemic and multidisciplinary perspectives are still emerging. What is striking is that the avenues identified are not independent but rather interconnected. For instance, the development of integrated frameworks cannot advance without broader sustainability metrics capable of capturing trade-offs across energy, water, and lifecycle impacts. Similarly, digital tools such as AI and digital twins will only deliver meaningful insights if they are embedded within such frameworks.

Another key observation is that the literature has largely focused on technological solutions, leaving governance, policy, and social aspects as secondary concerns. Yet these are often decisive in determining whether innovations scale beyond pilot projects. Without institutional support, regulatory incentives, and coordinated stakeholder action, many technical gains may remain confined to experimental settings. This underscores the importance of linking research on governance with technical innovation.

The table also shows that CE applications remain underdeveloped beyond energy recovery. The transition from a linear to a circular model requires rethinking not only how data centers consume energy but also how they manage materials, infrastructure design, and interactions with urban ecosystems. This opens a promising space for cross-sectoral collaboration between ICT, construction, and energy systems research.

Taken together, these insights suggest that future work should prioritize integration across dimensions, moving from isolated gains to systemic strategies that align data center growth with climate goals and CE transitions.

5 FINAL CONSIDERATIONS

This study provided an overview of sustainability practices in data centers, revealing two dominant lines of research: waste heat recovery and cooling optimization. Practices such as thermodynamic cycles, absorption chillers, and biogas integration demonstrate the potential to valorize residual energy (P1–P6), while digital optimization, economizers, and free cooling solutions (P7–P12) illustrate the diversity of strategies to improve efficiency. Together, these findings highlight that the academic debate has largely concentrated on the "hardware" of efficiency, with limited attention to water and carbon dimensions.

The main contribution to knowledge lies in consolidating fragmented evidence into a structured overview that identifies patterns, complementarities, and gaps. By explicitly linking practices to categories and performance indicators, this study advances conceptual understanding of green data centers. For practice, it offers a synthesized map of solutions that decision makers can adopt to enhance efficiency and reduce emissions, while underscoring the importance of contextual factors such as climate conditions and infrastructure integration.

Regarding the limitations, the study was restricted to Scopus and Web of Science databases and focused on peer-reviewed articles, which may have excluded relevant industry reports or grey literature. In addition, the analysis emphasized qualitative synthesis, leaving quantitative performance comparisons for future research.

The key take-away from this study is that data center sustainability cannot be achieved through isolated technical improvements alone. Future progress depends on integrating energy, water, and carbon metrics into systemic frameworks, linking technological innovation with governance and CE principles. By pursuing this direction, the sector can move from incremental gains to transformative strategies that align digital expansion with sustainability goals.

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