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Sustainable development strategies for smart sustainable campus operations: global trends, challenges and opportunities

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Higher Educational Institutions (HEIs) worldwide are increasingly adopting the Smart Sustainable Campus (SSC) model to drive sustainability across campus operations. This systematic literature review (SLR) critically examines global strategies, trends, challenges, and opportunities in SSC implementation, focusing on the five core operational domains: waste management, setting and infrastructure, energy management, water management, and sustainable mobility. Based on the PRISMA Flow Chart, the research examined 90 peer-reviewed publications dated 2015–2025, sourced from Scopus, Web of Science, ScienceDirect and Emerald Insight. The findings indicated that, despite breakthroughs already made, notably in energy management and intelligent infrastructure, gaps remain in integrated frameworks, standardised metrics, and comprehensive policy approaches. Financial constraints, technological differences, policy fragmentation, and data privacy are among the challenges common in a developing context. Yet, recent technological advances, such as Artificial Intelligence, the Internet of Things, blockchain, digital twins, cross-sector collaborations, and capacity-building efforts, offer a radically new possibility for SSC development. The study provides a detailed roadmap linking SSC operations to the United Nations Sustainable Development Goals (SDGs), positioning HEIs as pivotal agents in building sustainable, resilient, and inclusive academic environments.

KEYWORDS

energy management, smart sustainable campus, sustainable development goals, sustainable mobility, waste management, water management, green infrastructure, higher education institutions

1 Introduction

The emergence of Smart Sustainable Campus (SSC) represents a significant evolution in how higher education institutions (HEIs) will address challenges related to global sustainability (Hariram et al., 2023). Rooted in the principles of sustainable development, SSCs represent an institutional transition embedded with digital innovation and ecologically oriented campus activities (Santos, 2024). Factors such as environmental concerns, technological development, and international sustainability frameworks, including the United Nations Sustainable Development Goals (SDGs), the Talloires Declaration, and the UI Green Metric World University Rankings, have influenced the shift to SSCs, as asserted by Leal et al. (2021). These global agendas continue to encourage HEIs to become not only centres of knowledge creation but also operational exemplars of sustainability.

The SSC paradigm is broadly categorised into three major conceptual streams. The human-centric stream is the first, with an emphasis on behaviour change, stakeholder input, and equity (Atay et al., 2025). The second one is the techno-centric stream, which is characterised by the implementation of digital technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and big data analytics (Wen et al., 2023; Zaballos et al., 2020). The third, the post-anthropogenic stream, points to a more radical re-visioning of campuses as self-managing, adaptive ecosystems staying within global thresholds (Agarwal, 2023). Together, these streams frame the multidimensional nature of SSCs and emphasise the importance of aligning operations with ecological integrity, social well-being, and technological resilience. Across international literature, four major strategies for operationalising sustainability within HEIs have been identified: (1) education, (2) research, (3) community collaboration, and (4) campus operations (Dzhuguryan and Deja, 2021). This study specifically focuses on the fourth strategy, campus operations, which comprises five core indicators: energy; setting and infrastructure; water management; sustainable mobility; and waste management. These domains represent critical leverage points through which SSCs can influence environmental impact, institutional efficiency, and socio-cultural transformation (Pandiyan et al., 2024; Rehman et al., 2024; Rodríguez et al., 2023).

Ayyash and Salah (2025) noted that, despite the proliferation of case studies and institutional reports, the SSC literature remains fragmented. Few studies have offered integrative perspectives spanning all five operational domains, particularly through the lens of global diversity and policy alignment (Stuckrath et al., 2025; Marín-González et al., 2022; Adenle et al., 2021). Furthermore, while some campuses have achieved technological sophistication, others remain constrained by limited resources and policy inertia. Ferraris et al. (2020) expressed that a critical synthesis of global trends, gaps, and innovations is necessary to advance theory and practice in SSC development. Kim et al. (2021) revealed that the literature reveals a misalignment between the technological and socio-political dimensions of SSC implementation. While advanced digital solutions are increasingly available, their deployment often lacks institutional coherence, stakeholder engagement, and contextual sensitivity (Oliveira and Proença, 2025; Muqeeet et al., 2022; Oyedepo et al., 2021). In addition, current research frequently isolates operational domains rather than examining them as an integrated system, leading to siloed approaches and suboptimal outcomes.

This study investigates sustainable development strategies for Smart Sustainable Campus operations, emphasising global trends, challenges, and opportunities across core operational domains. To realise this goal, the research will be informed by the following research questions:

- i) How are Smart Sustainable Campuses defined and operationalised globally across waste, energy, infrastructure, water, and mobility domains?
- ii) To what extent do these operational practices align with the SDGs and international sustainability declarations?
- iii) What are the key institutional, technological, and socio-cultural challenges and opportunities in the adoption of SSC strategies?

1.1 Emergence of the smart sustainable campus

According to Martínez et al. (2021), the concept of the Smart Sustainable Campus (SSC) represents a dynamic intersection between

sustainability imperatives and technological innovation in higher education institutions (HEIs). Its emergence is rooted in two foundational trajectories: the environmental sustainability movement in academia and the digital transformation of institutional operations (Rane, 2023). Historically, HEIs have played an instrumental role in advancing the sustainability discourse, particularly since the 1990 Talloires Declaration, which was the first official commitment by HEI leaders to environmental sustainability (Lan and Shizhu, 2025). It was then followed by such global initiatives as the United Nations Decade of Education for Sustainable Development (2005–2014), Rio + 20 Outcome Document (2012) and acceptance of Sustainable Development Goals (SDGs) in 2015 that all in one strengthened the requirement of being able to incorporate sustainability in educational processes, as well as operational and community engagement (Sugandha et al., 2025; Reihaneh and Marzieh, 2023; Hiltunen et al., 2022).

Concurrently, Sen et al. (2021) pointed out that the rapid growth of digital innovations, including the Internet of Things (IoT), Artificial Intelligence (AI), cloud computing, and data analytics, has enabled campuses to digitalise the operations and streamline the management of resources in real-time (Alshuwaikhat et al., 2022). This digital transformation was first framed under the “smart campuses” tag, centring on efficiency and user experience. Nonetheless, the increased understanding of climate change, resource depletion, and equity concerns led to the synthesis of the smart and sustainable paradigms, which resulted in the emergence of the SSC model complex, technology-enhanced, and sustainability-centred campus framework (Negri et al., 2021). The SSC therefore presents a strategic transition from linear, resource-use-based campuses, bound by compartments and compartmentalised governance, to adaptive, participatory, circular systems in line with planetary boundaries and socio-technical resilience (Mohammed et al., 2022). This is because of growing external pressures on HEIs to reduce their environmental footprint, model climate leadership, and educate future sustainability practitioners (Pacini et al., 2025). As such, the SSC has come as not only an upgrade of technology but also a revolutionary institutional design, which has multi-dimensional repercussions on the structure of infrastructure, morale of governance, teaching and learning methods and interactions with the stakeholders (Jiao et al., 2024; Zainullah et al., 2024; Yan et al., 2023).

1.2 Conventional campus to smart sustainable campus

According to Malagnino et al. (2021), transitioning from a conventional campus to a Smart Sustainable Campus (SSC) is not just about technology; it is a paradigmatic shift of how HEIs view and operationalise sustainability. Traditional campuses operate on fragmented systems in which facilities management, academic departments, and student affairs feel like silos, with no shared sustainability objectives or interoperable sustainability data (González-García et al., 2023). Such campuses are traditionally described by operational inefficiencies in the usage of resources, numerous fixed assets, and responsive approaches to maintenance and environmental responsibility are minimal. In addition, as asserted by Rieckmann and Bormann (2020), sustainability efforts, when present, are more project-driven than systemic, lacking institutional anchoring or long-term strategic planning. The SSC model envisions the campus as a living laboratory (Azzali and Sabour, 2018), particularly a dynamic, data-rich environment that incorporates sustainability and technology at every level of operation

(Adeyemi et al., 2018). At the core of this model, there lies the idea of interconnectivity, as physical systems (e.g., energy grids, water infrastructure, transportation networks), digital systems (e.g., IoT sensors, campus apps, cloud platforms), and social systems (e.g., student and staff behaviours, governance frameworks) all interact collectively to enable the system to adapt through decisions and continual enhancements (Weil et al., 2023; Jawad et al., 2023; Esfilar et al., 2021).

Rey-Hernández et al. (2023) underscored that a significant distinction lies in how governance and sustainability evaluation are approached. Whereas traditional models still heavily rely on manual audits and trailing indicators, SSCs use real-time dashboards and predictive analytics to monitor performance and simulate interventions (Kolokotsa et al., 2016). This empirical framework is capable of analysing in detail the patterns of resource consumption; identifying inefficiencies early enough is the foundation of designing policies based on evidence. Pan et al. (2023) stated that integrating Building Information Modelling (BIM), digital twins, and smart metering enables advancements in SSC operations. As SSCs become able to transcend the reactive management practices of conventional campuses and move toward anticipatory and resilient operations (Domínguez-Bolaño et al., 2024; Olawumi et al., 2023; Alshuwaikhat et al., 2022). Alrashed (2020) stated that, on a par with the societal change, SSCs aim to influence is the cultural shift. Sustainability in conventional settings is often the responsibility of a specific unit or office. In SSCs, sustainability is institutionalised as a cross-cutting principle embedded in teaching and research agendas, operational protocols, and student life (Batal et al., 2024; Shao and Min, 2024; García-Monge et al., 2023). It is a holistic approach that encourages taking shared responsibility and enables all stakeholders to play a role either in bringing about sustainability results, or it may be a change in changing behaviour, innovations, or advocacy of policy outcomes (Zhou and Zheng, 2024; Ramírez et al., 2023; Mohammed et al., 2022). The transition towards SSCs is an integrated reorganisation of the university as a knowledge organisation and a sustainability player (Doaa and Davies, 2025; Nkem et al., 2019). It puts HEIs to the test by requiring them to align their operational logic with global sustainability demands, the trend toward digital technologies, and evolving stakeholder expectations.

1.3 Theoretical framework

The implementation of Smart Sustainable Campus (SSC) initiatives is grounded in multidimensional theoretical thinking that goes beyond describing only the structural and operational aspects of campus transformation, to the socio-cultural and institutional contexts upon which they are grounded (Ajiboye et al., 2022). The inter-related theories of Triple Bottom Line (TBL), Socio-Technical Systems (STS) Theory, and Diffusion of Innovations (DoI) Theory provide guiding insight into the planning, implementation and assessment of SSCs (Xie et al., 2023).

The foundational framework of the Triple Bottom Line (TBL) forwarded by Elkington (1997) enables a broader sustainability assessment than economic assessment. It suggests that any system that can be sustained must achieve a balance among three pillars: environmental integrity, social equity, and economic viability (Dawodu et al., 2022). Lim et al. (2022) asserted that when applied to SSCs, the TBL lens enables HEIs to assess whether campus operations (e.g., energy systems, water use, infrastructure, mobility, and waste management) not only reduce ecological impact but also enhance social inclusion

(e.g., accessibility, participation) and institutional efficiency (e.g., cost savings, resource optimisation). For instance, green buildings can save emissions (environmental), improve the indoor environment with regard to health (social), and save utility costs (economic), hence meeting the TBL mandate.

The Theory of Socio-Technical Systems (STS) is complementary to the TBL, as it focuses on the interface between technological innovation and societal structures (Ahlborg et al., 2019). Sony and Naik (2020) stated that the STS theory is a concept formulated in organisational research, arguing that technology systems are never isolated and are deeply embedded and shaped by institutional cultures, governance structures, and user behaviours. In SSCs, implementing smart grids, IoT sensors, or mobility platforms must be coordinated with the university's social architecture, how it decides, its stakeholders' values, and the preparedness of its institution (Akbar et al., 2023; Sangita and Sakharle, 2022). STS theory therefore underscores the need to change technical infrastructures and human systems concurrently for effective SSC transformation.

Diffusion of Innovations (DoI) Theory, first presented by Rogers (2003), provides some useful insights on the process of diffusion of innovations (SSC-related or otherwise) across and among institutions. Perceived advantage, compatibility with existing systems, trialability, observability, and complexity are among the factors this theory focuses on in the adoption context (Duanmu and Chai, 2025). Single-source computing settings in SSC environments change agents, including sustainability champions or IT departments, are often early adopters (pioneers) of technologies, such as digital twins or energy dashboards, that tend to spread to other departments (Liu and Ren, 2020; Liu et al., 2020). Communication channels, peer influence, and institutional culture are also mentioned in the theory as factors that underscore speed or slowness in the adoption of SSCs (Ivars-Baidal et al., 2023).

These frameworks, taken cumulatively, demonstrate the significance of systemic thinking in SSC planning (Santos, 2024; Sima et al., 2022; Françozo et al., 2021). Although TBL guarantees adherence to sustainability outcomes, STS provides an operational interface between technology and organisation, and DoI provides the temporal and cultural pathways for the diffusion of SSC. The theories point out that SSC success cannot be reduced solely to the deployment of appropriate tools, but rather to the creation of the right institutional environments that are flexible, participatory, and future-oriented.

1.4 International declarations, indicators, and institutional commitments

The process of development and introduction of the Smart Sustainable Campuses (SSCs) is more and more determined by policy frameworks and institutional ranking rules of the global community, which demand thorough incorporation of sustainability in the work of higher education establishments (Rieckmann and Bormann, 2020). Such international declarations and indicator-based assessments are not only sources of normative guidance, but they also give universities incentives to measure, benchmark, and enhance their sustainability performance (Doaa and Davies, 2025). The framework most relevant to sustainable development is the United Nations Sustainable Development Goals (SDGs), adopted in 2015, which provide a universal blueprint of 17 goals and 169 targets to be achieved in sustainable development (Lan and Shizhu, 2025). Higher education institutions are increasingly aligning their SSC strategies with key SDGs, including SDG 4 (Quality Education), SDG 7 (Affordable and

Clean Energy), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). For instance, the shift of a HEI toward renewable energy sources or the zero-waste movement has a direct, positive impact on several SDG goals, reinforcing their universal relevance (Malagnino et al., 2021).

The Talloires Declaration, the first declaration by HEI leaders promising to commit higher education to sustainability, is another policy tool on which the new policies are based (Mai et al., 2024). More than 500 HEIs signing it require environmental literacy as a component of instruction, operations, and informing communities. This declaration laid the groundwork for SSCs by formalising sustainability as a core institutional mandate, rather than an ancillary activity (Lan and Shizhu, 2025). In parallel, ranking systems such as the UI Green Metric World University Ranking and the Sustainability Tracking, Assessment and Rating System (STARS) have played a critical role in shaping SSC operational indicators (Horan and O'Regan, 2021). Green Metric, for instance, evaluates HEIs across six criteria, which are setting and infrastructure, energy and climate change, waste, water, transportation, and education or research (Boiocchi et al., 2023). These indicators directly mirror the core operational domains examined in this study and provide HEIs with quantitative benchmarks for performance improvement.

National-level initiatives also shape SSC development. In countries like the United Kingdom, the Carbon Trust Standard for Universities and the Environmental Association for Universities and Colleges (EAUC) have institutionalised sustainability reporting and carbon reduction targets (Saha et al., 2020). Similarly, Australia's TEFMA (Tertiary Education Facilities Management Association) promotes smart campus technologies to improve operational performance (Mahmoud et al., 2024). In emerging contexts, governments have begun to integrate SSC goals into broader national sustainability agendas, though funding, infrastructure, and monitoring gaps remain. Despite these efforts, challenges persist. Numerous HEIs face the dilemma of scattered implementation, as proclamations of sustainability are issued but not carried through in operational changes (Ramos et al., 2015). Others report difficulties in data collection, indicator standardisation, and inter-departmental coordination. However, global structures have driven a turnaround in universities' ideas and quantification of sustainability (Shu and Tian, 2024). Notably, they promote competition, transparency, and networks of learning. Also, they stimulate institutions not only to report their progress but also to innovate in achieving global common purposes (Lim et al., 2022).

In this regard, the SSCs act not only as an operational model but also as an accountability entity, converting global sustainability mandates into practical campus-based activities (Ayyash and Salah, 2025). The ability of a university to meet or exceed these benchmarks increasingly defines its reputation, funding potential, and global partnerships, thereby underscoring the strategic importance of SSCs in 21st-century higher education (Sangita and Sakharle, 2022).

1.5 Global trends and frameworks across Core operational domains

Smart Sustainable Campuses (SSCs) operate at the convergence of environmental stewardship, the digital transformation, and higher education reform (Gu et al., 2025). Xie et al. (2023) stated that there are globally unique trends across the five operational domains: waste management, setting and infrastructure, energy management, water

management, and sustainable mobility. The trends indicate not only technological advances but also institutional responses to regulatory pressures and student activism campaigns, on the one hand, and to competitive sustainability benchmarking of institutions, on the other.

i Waste Management

Waste management in SSCs has evolved beyond basic recycling to incorporate smart waste tracking systems, behaviourally informed interventions, and zero-waste targets (Panaite et al., 2024). HEIs such as the University of California have been embracing holistic Zero Waste by 2020 policies, which include the deployment of smart bins with IoT sensors, trash analytics solutions and campus-wide education campaigns (Rodríguez-Guerreiro et al., 2024). Recycling programs, reusable packaging systems and composting programs are also becoming typical in food services and residential halls (Okoro et al., 2020; Olukanni et al., 2018). Globally, there is growing emphasis on circular economy models, in which campus waste serves as an input for energy (e.g., biogas) or agriculture (e.g., compost), especially in European and Southeast Asian HEIs.

ii Setting and Infrastructure

Sustainable campus settings are characterised by the integration of green design principles with intelligent building management (Ribeiro et al., 2018). Standards such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) guide the construction and retrofitting of academic facilities. In advanced SSCs, smart buildings utilise real-time environmental sensors and AI algorithms to regulate lighting, HVAC systems, and occupancy schedules (Oyedepo et al., 2019). Additionally, digital twins (virtual models of physical spaces) are increasingly used for predictive maintenance and energy simulations. At the planning level, green campus masterplans incorporate biodiversity conservation, water-sensitive landscaping, and climate-resilient infrastructure (Hussain and Sheikh, 2023; Pankaj et al., 2024). Although LEED and BREEAM are widely referenced in past SSC studies as standards of sustainability, their applicability to campus-wide assessments remains limited. These frameworks are primarily design-based certifications which focus on single buildings, rather than performance-oriented instruments that can work in multi-building university environments. Basheer et al. (2025) noted the fact that their reliance on static rating criteria makes them less effective in the capturing of dynamic sustainability performance metrics across various campus systems. Therefore, future SSC assessment frameworks must have Key Performance Indicators (KPIs) that monitor continuous performance in such aspects as energy, water, and transportation, rather than focusing mainly on design intentions.

iii Energy Management

Among the most advanced domains, energy management in SSCs combines on-site renewable generation with smart grid integration and AI-driven efficiency tools (Nkem et al., 2019). Leading examples include Stanford University's Energy System Innovations (ESI), which shifted the campus from fossil fuels to electricity-based heating and cooling, resulting in a 68% reduction in carbon emissions (Wang et al., 2023). IoT-enabled

energy dashboards allow real-time monitoring by both facility managers and students, often paired with gamification to promote behavioural change. In the Global South, cost-effective solar PV installations and microgrids are expanding energy access while promoting climate action (Rodgers, 2021).

iv Water Management

Smart water management in SSCs emphasises efficiency, reuse, and resilience. IoT-based systems detect leaks, track usage, and optimise irrigation in real-time based on soil moisture and weather data (Shboul et al., 2023). Universities in water-scarce regions such as Australia and the Middle East have pioneered rainwater harvesting, greywater recycling, and desalination pilots (Jiao et al., 2024). Furthermore, water footprints are now reported alongside carbon footprints in sustainability audits, highlighting the growing importance of water stewardship. Campus stormwater management is also evolving, with permeable pavements and bioswales integrated into infrastructure to mitigate flood risks and improve aquifer recharge (Rey-Hernández et al., 2023).

v Sustainable Mobility

Sustainable mobility is increasingly framed within transport decarbonisation, active commuting, and the mobility-as-a-service (MaaS) paradigm. SSCs promote walking and cycling through dedicated lanes, secure bike storage, and incentive programs (Olawumi et al., 2023). The deployment of electric vehicle (EV) infrastructure, such as charging stations and EV-sharing schemes, is expanding rapidly. Smart mobility platforms, often app-based, offer real-time shuttle tracking, ride-sharing, and route optimisation. Campuses such as those in Singapore and the Netherlands are leading in integrating low-carbon transportation systems with smart data analytics to reduce traffic congestion and emissions (Santos, 2024).

vi Emerging Operational Domains

Recent studies expand the operational model of Smart Sustainable Campuses (SSCs) to include learning environments and indoor environmental quality (IEQ) as critical aspects of sustainability (Azzali and Sabour, 2018; Jiang and Kurnitski, 2023; Shao and Min, 2024). Sustainable learning environment focuses on emerging modes of teaching, interactive facilities and digital learning facilities that aids awareness and education on sustainability (SDG 4: Quality Education). Similarly, IEQ encompasses air quality, lighting, acoustics and thermal comfort, all of which has a significant influence on the way people feel, think, and how productive they are (SDG 3: Good Health and Well-Being). The incorporation of these domains link SSC frameworks to holistic sustainability objectives that focus on the environmental outcomes as well as on human experience, therefore reinforcing the idea of the human-centricity of SSC conceptualisation.

vii Expanded SDG Alignment Across SSC Operational Domains

The SSC operating framework aligns with the broader United Nations Sustainable Development Goals (SDGs). In addition to the key objectives of SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), SDG 12

(Responsible Consumption and Production), and SDG 13 (Climate Action), SSCs contribute to SDG 4 (Quality Education) (through creation of learning-oriented environments) and SDG 3 (Good Health and Well-Being) through health promoting and the provision of safe campus spaces (Basheer et al., 2025). This total conformity demonstrates the significant role SSCs play in transforming both infrastructural and human dimensions of sustainability in higher education.

1.6 Gaps in the literature and conceptual challenges

Despite the expanding body of research on Smart Sustainable Campus (SSC) operations, several critical gaps remain unaddressed, reflecting limitations in scope, methodological diversity, and conceptual coherence.

i Fragmented Domain Integration

Most studies focus on single operational domains, such as energy or infrastructure, without accounting for interdependencies across domains (Olawumi et al., 2023). This single-focus approach obscures synergies and trade-offs, limiting understanding of holistic SSC effectiveness. Integrated assessments remain scarce, hindering the development of comprehensive SSC evaluation frameworks (Pan et al., 2023).

ii Evaluation Metrics and Benchmarking Limitations

While indicator systems such as UI Green Metric and STARS provide structured benchmarks, they often suffer from inconsistency in reporting parameters and lack longitudinal data (Makhoul, 2022). These dashboards generally capture “what is being done” rather than “what has been achieved,” making it difficult for institutions to measure long-term impacts over time. The absence of standardised, globally adopted performance indicators remains a collective barrier (Cunha et al., 2024).

iii Underrepresentation of Post-Anthropogenic Perspectives

Existing literature privileges techno-centric and human-centric narratives but rarely engages with post-anthropogenic perspectives (Cherp et al., 2018). These perspectives foreground non-human considerations: biodiversity, ecosystem integration, and planetary health. As SSCs evolve to meet broader climate and ecological imperatives, the absence of this dimension limits the potential for truly sustainable transformation (Ramírez et al., 2023).

iv Regional and Socio-economic Biases

A disproportionate number of SSC case studies originate from developed economies (Mihic et al., 2019). Universities in Africa, Latin America, and Southeast Asia are underrepresented, yet these regions face the most severe sustainability challenges and have unique constraints. The resulting research bias limits global generalisability and obscures context-specific innovations, such as solar-powered purification systems or decentralised water treatment solutions (Alrashed, 2020).

v Behavioural Dimensions and Stakeholder Engagement Gaps

Although several studies acknowledge the role of stakeholder participation, empirical research on how changes in student,

faculty, and staff behaviour influence SSC success is limited (Amaral et al., 2020). Behaviourally informed interventions (e.g., gamification, participatory planning) are often described without rigorous evaluation. This gap reduces the practical relevance of recommendations for real-world SSC scaling and adoption (Das et al., 2022).

vi Ethical and Data Governance Considerations

The increasing digitisation of campus systems raises ethical concerns regarding privacy, consent, and transparency (Adeyemi et al., 2018). Few studies engage deeply with these issues. Clear protocols for data ownership, usage policy, and privacy are frequently omitted from SSC design frameworks, yet they become critical for trust, acceptance, and sustainability (Françoze et al., 2021).

2 Methodology

The study used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure a comprehensive, transparent and replicable review process (O'Dea et al., 2021). The methodology was organised in terms of four major phases, namely, identification, screening, eligibility, and inclusion, which allowed selecting relevant research on Smart Sustainable Campus (SSC) operation in precise terms of waste management, setting and infrastructure, energy management, water management, and sustainable mobility in a rigorous way (Polin et al., 2023).

2.1 Research design

Guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, this study made use of a Systematic Literature Review (SLR) approach (Agrawal et al., 2024). This method allows for a thorough and replicable synthesis of peer-reviewed studies with the goal of identifying trends, conceptual gaps, and emergent strategies in Smart Sustainable Campus (SSC) operations (Chagnon-Lessard et al., 2021). The rapidly evolving and interdisciplinary nature of SSC research, covering fields including environmental science, education, engineering, and digital technology, makes the SLR design especially well-suited to this study.

2.2 Data sources and search strategy

To gather exhaustive data, several academic databases, including Scopus, Web of Science, ScienceDirect and Emerald Insight, were employed. These four academic databases were selected for their wide and detailed coverage of multidisciplinary research spanning sustainability, higher education, and technological innovation research. The search technique used a combination of Boolean phrases and words to narrow search results (Karale, 2021). Expression used as keywords were combinations of the words, such as; ("smart sustainable campus" OR "smart campus" OR "sustainable campus") AND ("energy management" OR "waste management" OR "water management" OR "infrastructure" OR "mobility") AND ("higher education" OR "university" OR "college"). The search was restricted to English-language peer-reviewed journal articles and conference papers published

between 2015 and 2025 to capture contemporary developments while allowing temporal breadth for trend identification.

2.3 Inclusion and exclusion criteria

In order to obtain relevance and quality of information, the following inclusion and exclusion criteria were set up as shown in Table 1.

2.4 Data extraction and analysis

The study was designed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and rigour in the literature selection process. A thorough search was conducted across four key academic databases: Scopus, Web of Science, ScienceDirect, and Emerald Insight. Title/Abstract/Keyword search terms applied in the search strategy included a combination of terms that were relevant to the study. In the first search, 518 articles were retrieved. Relevance and quality were provided by the following filters: Language: English only, Source Type: Peer-reviewed journal articles, Document Type: Full research articles and review papers, Publication Period: 2015–2025. These criteria were applied, and the articles were narrowed down to 450. The second step involved screening the remaining articles relevant to the research topic. Only studies that discussed both smart cities and sustainability, as well as environmental sciences, with respect to the research issue were considered. Any articles that failed to meet such thematic requirements were left out. After this step, 252 papers based on appropriate methodologies and presenting outcomes consistent with the objectives of the research were selected. A further screening step involved applying a time-frame criterion (2015–2025) to ensure the analysis focused on contemporary developments. Out of these 252 articles, 162 qualified on this criterion. 72 articles were excluded for reasons such as insufficient operational focus (34 articles), lack of higher education context (23 articles), and non-English language (15 articles). Content analysis was conducted on the identified articles, from which information was extracted and classified into research themes. In the final stage,

TABLE 1 Inclusion and exclusion criteria table.

S/N	Inclusion criteria	Exclusion criteria
i	Peer-reviewed journal articles	Non-peer-reviewed material such as editorials, book chapters, or technical reports
ii	Publications in the English language	Publications not in the English language
iii	Explicit reference to one or more of the five operational domains: energy, setting/infrastructure, water, waste, or mobility	Duplicates across databases
iv	Articles published between 2015 to 2025	Articles lacking methodological rigor or empirical evidence

90 articles were deemed most relevant for in-depth analysis and synthesis. These articles presented in [Appendix](#) were examined to: identify dominant themes in the literature, provide a descriptive analysis of current trends and highlight existing gaps and propose future research directions. This PRISMA multiple-phased process is illustrated in [Figure 1](#) (PRISMA Flow Diagram), ensuring that the study selected only high-quality, relevant, and recent literature for the systematic review.

2.5 Quality assessment

To assess the quality of the studies included in the synthesis, a standardised appraisal checklist was used to ensure the findings were reliable. This checklist considered items such as research design, methods of data collection, rigour in analysis, and the relevance of the conclusions to SSC operations.

2.6 Limitations

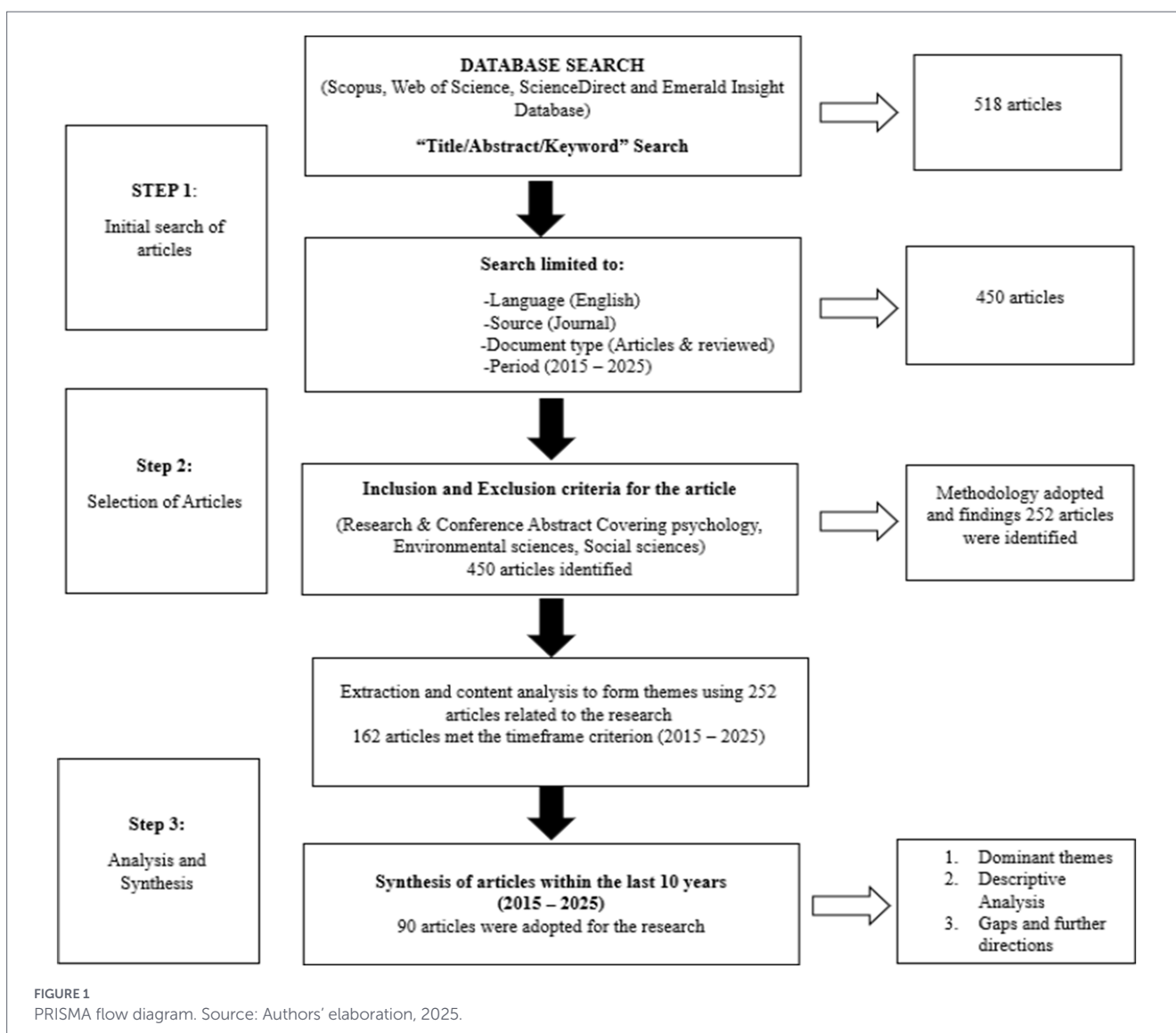
Using a methodology that provided extensive examination, a few limitations were identified. The limitations of English-language

publications may have excluded relevant studies conducted in other languages. Also, the reliance on academic databases may overlook grey literature and practical reports that could offer valuable insights. By adhering to the PRISMA framework and using a combination of rigorous selection and analysis methods, this study will conduct a high-quality synthesis of existing knowledge on sustainable development strategies for SSC operations, offering a solid foundation for future research and policy formulation.

3 Findings and discussion

3.1 Overview of selected studies

Following the rigorous PRISMA methodology, 90 publications were identified as relevant to the Smart Sustainable Campus (SSC) across waste management, setting and infrastructure, energy management, water management, and sustainable mobility. The studies conducted were largely geographically diverse, with research across North America, Europe, Asia, Africa, and Australia conducted in both



developed and developing settings. The study distribution revealed that energy management and establishment of infrastructure played a leading role, followed by water and waste management and sustainable mobility (Rodríguez et al., 2023; Malagnino et al., 2021; Rodrigues and Franco, 2021). The emphasis on energy and infrastructure aligns with worldwide climate goals and the ease with which return on investment (ROI) can be measured in these sectors. Most research used mixed-methods or case study designs, therefore emphasising both quantitative performance measures and qualitative insights from stakeholder involvement (Mohammed et al., 2022; Negri et al., 2021; Ferraris et al., 2020). Some papers employed comparative analysis, examining the efficacy of SSC initiatives across diverse geographic, institutional size, and technical capability (Rehman et al., 2024; Yan et al., 2023; Kim et al., 2021). A significant trend across the literature is the growing use of real-time data collection and analysis, indicating a shift toward evidence-based, sustainable management.

3.2 Thematic findings by operational domain

3.2.1 Waste management

The reviewed studies show that the use of smart technology has greatly transformed SSCs' waste management techniques (Olawumi et al., 2023; Wang et al., 2023; Hiltunen et al., 2022). Key strategies include smart bins equipped with fill-level sensors, waste-sorting systems, and digital tracking of garbage-generating trends. According to Anthony (2020), institutions with policies that include thorough recycling programs, composting operations, and zero-waste policies have also been able to demonstrate noteworthy reductions in landfill inputs and expenditure decrease.

Amaral et al. (2020) stated that a machine learning-backed, sophisticated waste classification system is becoming an innovative method to automatically classify waste types and send them for corresponding processing. HEIs like the National University of Singapore and the University of California locations have been pioneering AI-powered trash-determining kiosks, in which participants are rewarded and incentivised for accurate waste disposal. Other studies claim that behavioural change programs constitute a critical supplement to technological interventions (Stamopoulos et al., 2024; de Puppim Oliveira et al., 2022; Pereira et al., 2021). Encouragement for students to adopt more sustainable waste habits has come from digital interaction and gamification. Leticia et al. (2023) asserted that still challenges exist, even with these advancements. Many HEIs lack the funding or institutional planning necessary to install more sophisticated smart waste systems (Das et al., 2022). Optimal performance is also hampered by fragmented data systems and limited stakeholder awareness (Liu et al., 2024; García-Monge et al., 2023). Furthermore, there are institutions with recycling contamination issues stemming from inadequate waste separation, underscoring the importance of continuous training and community engagement.

3.2.2 Setting and infrastructure

Research includes the use of green building standards, such as LEED and BREEAM, along with smart building technologies, in the campus setting and infrastructure (Ajaj et al., 2025). Jiang and Kurnitski (2023) highlighted that, while LEED and BREEAM

frameworks provide valuable guidance for green building design, there exist limitations in their applicability to campus-wide assessment, because they are not directly based on performance alone, nor oriented towards multi-based campus systems. Heating, ventilation, and air conditioning (HVAC) and automated lighting increase energy efficiency and occupant comfort. Since infrastructure planning, performance monitoring, and sustainability assessments are important parts of infrastructure studies, the concepts of digital twins and building information modelling (BIM) have come to play significant roles (Shu and Tian, 2024).

Moreover, newer projects increasingly incorporate biophilic design principles to foster student well-being and enhance environmental connectivity (Anthony, 2020). Scandinavian and Japanese campuses are good examples of incorporating natural elements such as daylighting, green roofs, and growing indoor plants into their smart building strategies. The energy-saving methods are not only energy-efficient but also promote mental health, a facet of campus sustainability that is rarely considered (Abu-Rayash and Dincer, 2023). Oyadeyi and Oyadeyi (2025) stated that another emerging theme is infrastructure resilience to the effects of climate change. Australian and southwestern US case studies report on climate-adaptive design, like flood-resistant walkways, modular green wall systems to cool cities and permeable paving systems. The use of performance dashboards accessible to both facilities managers and campus users promotes transparency and accountability in resource use (Gu et al., 2025).

3.2.3 Energy management

Energy management is the most widely covered domain in the literature. SSCs deploy smart grids, renewable energy sources and energy storage solutions (Oyadeyi and Oyadeyi, 2025). Studies document the use of AI and machine learning algorithms to optimise energy consumption and predict peak demand periods. These approaches contribute to significant reductions in greenhouse gas emissions and operational energy costs (Urbano et al., 2025; Oyedepo et al., 2021). Notably, some universities have established energy microgrids that allow for energy self-sufficiency and enhanced resilience during power outages (Pereira et al., 2021). Stanford University, for example, has implemented an innovative energy system combining solar generation, chilled-water loops, and predictive software to reduce its greenhouse gas emissions by over 60% (Kourgiouzou et al., 2021). Meanwhile, universities in Germany and the Netherlands explored energy-neutral or positive-energy campuses through extensive retrofitting and the smart integration of geothermal and wind energy.

3.2.4 Water management

The study on water management in the SSCs focuses on smart water meters, leak detection, and automated weather-driven irrigation systems using soil moisture sensors (Sugandha et al., 2025). Harvesting of rainwater and recycling of grey water are practised more, especially in regions experiencing water scarcity. These measures improve water conservation and sustainability in the operations on the campus. Indian and sub-Saharan African studies noted that decentralised solutions to water are required because of infrastructural constraints (Ajaj et al., 2025; Das et al., 2022). Constructed wetlands are among the nature-based solutions implemented at some universities, where

greywater can be treated on-site. In wealthy settings, intelligent water dashboards help facility representatives perceive wastefulness and apply corrective measures as soon as possible. The other trend is the convergence of water systems and wider campus resource platforms, so that water, energy, and occupancy data could be traced together (Pereira et al., 2021). Students also demonstrate their activities on water conservation through research, which creates awareness and instills a culture of responsibility (Reihaneh and Marzieh, 2023).

3.2.5 Sustainable mobility

Sustainable mobility is promoted by popularising cycling, walking, and the use of electric vehicles (EVs) on campus (Abu-Rayash and Dincer, 2023). Researchers draw attention to the emergence of bike-sharing systems, bicycle-only lanes, EV charging networks, and mobility applications capable of ensuring real-time routing and time-bound transportation planning (Amaral et al., 2020). These programs minimise the campus-generated carbon footprint and promote a healthier commuter lifestyle (Okeniyi et al., 2018). Universities in Netherlands and Denmark lead in incorporating of cycling as a mode of transportation. In comparison, institutions in automobile-centred areas such as the U.S. and the Middle East pay more attention to electric bus shuttles and smart parking (Amr et al., 2021). Congestion pricing or bans on access to specific vehicles are in place in some campuses to minimise the use of vehicles that use internal combustion (Pan et al., 2023). Mobile applications that combine transit data with gamified incentives have been demonstrated to encourage more students to use more sustainable means of transport (Domínguez-Bolaño et al., 2024). However, issues of accessibility remain a problem, especially to students with disabilities, or those campuses that are not well developed with respect to pedestrians.

3.3 Trends and innovations

Among trends that emerged in the studies, one can note the connection of ICT and sustainability reporting which is not well-developed yet (Agarwal, 2023), the creation of dashboards allowing tracking the use of various resources at the campus level and the use of gamification as the methods of encouraging students and staff members to embrace sustainable behaviours (Zyoud and Zyoud, 2025). Cross-campus teamwork and data exchange efforts are also gaining popularity, facilitating benchmarking and peer-to-peer learning. There are some institutions that have opened SSC access platforms through which data in energy, water, and mobility systems can be accessed publicly to use in education and research (Žalėnienė and Pereira, 2021). In a more specific sense, Clement et al. (2023) stated that the use of ICT in SSCs is evolving beyond simple monitoring to integrative platforms that incorporate a wide range of sustainability indicators. The developed platforms enable real-time feedback on energy and water consumption, waste production, and mobility patterns. Advanced data visualisation formulas, like dashboards and infographics, give both students, faculty, and administrators actionable steps based on data analysis that can better inform policy placements and behavioural change (Sharifi et al., 2024). Such openness allows establishing accountability and participation, which are two key principles of effective governance of campus sustainability.

Verdejo et al. (2022) highlighted that gamification, the use of game design elements in non-game environments, has proven to be a powerful influencer of behaviour change. HEIs have begun introducing applications and platforms that allow people to earn rewards for participating in environmental tasks, such as reducing electrical

consumption, using reusable water bottles, or commuting to campus by bicycle (Kaiser and Deb, 2025). Such programs create an atmosphere of competitiveness and neighbourhood interest and lead to greater material sustainability for campus stakeholders. Companies have shown greater compliance and enthusiasm for participating in environmental activities when gamification is used (Tan and Taeihagh, 2020). In addition to internal innovations, sustainability frameworks are also being explored on campuses (Ribeiro et al., 2021). Participation in peer benchmarking programs, including those organised within networks such as the International Sustainable Campus Network (ISCN) and the Association for the Advancement of Sustainability in Higher Education (AASHE), enables institutions to benefit from sharing others' experiences (Reimers, 2024). These partnerships lead to the improved design of policies, the spread of innovations, and the existence of repositories of best practices that are shared.

From a social innovation perspective, SSCs are developing novel ways of interaction between the campus communities and the larger cities (Da Costa, 2025). Smart transportation systems that connect university shuttles to city transit systems, community composting networks, and water-testing projects implemented by community members are examples of how SSCs are redefining the boundaries between campus and community (Shao and Min, 2024). Such hybrid models advocate inclusive innovation and strengthen the civic mission in higher education.

3.4 Regional disparities and contextual challenges

The analysis revealed an imbalance in the implementation of SSCs between developed and developing regions. The presence of more comprehensive and technology-intensive strategies of SSC is usually enabled by access to superior digital infrastructure, greater institutional capacity, and diverse funding sources that institutions in developed economies typically enjoy (Bashir et al., 2023). The national and regional policies to support these universities typically emphasise environmental sustainability and digital invention, thereby creating an empowering setting for the creation of smart campuses (Verdejo et al., 2022). Conversely, HEIs in the developing nations exhibit substantial systemic limitations that hinder the application of SSC (Ribeiro et al., 2020). These are financial limitations, political will, and deficient or outdated technical infrastructure. These challenges are worsened by the lack of long-term sustainability planning and the fragmentation of institutions (Serafini et al., 2022). Furthermore, the digital divide is a major obstacle, as most institutions are still not equipped with the most basic ICT infrastructure to collect, analyse, and automate data in real time.

According to Papantoniou et al. (2020), the adoption of SSC is also affected by cultural, institutional and governance issues. In a number of contexts, sustainability remains a marginal issue, in second place to the institution's conventional academic and administrative missions (Herth et al., 2024). For SSC strategies not to be fragmented or superficial, they strongly require leadership commitment and organisational alignment. Long-term sustainability projects may be disrupted by political instability and the incessant turnover of institutional leadership, creating a climate of uncertainty that discourages investment and innovation (Abo-Khalil, 2024). Silva-da-Nóbrega et al. (2022) opined that, in spite of these difficulties, the Global South is not devoid of innovation. Quite the opposite is happening: numerous HEIs are experimenting with low-cost, high-impact, localised solutions. For instance, the implementation of solar-powered drinking water

purification systems, decentralised composting units, and offline data logging devices demonstrates that sustainability is possible even under strict constraints. These community-based innovations are often the result of student-driven initiatives or partnerships with local communities and non-governmental organisations, demonstrating the potential of inclusive and context-specific approaches (Tan and Taeihagh, 2020).

The disparities in SSC implementation across regions reflect broader socio-economic and governance inequalities (Shao and Min, 2024). While the developed world can afford to undertake sophisticated, data-driven sustainability initiatives, the developing world faces a range of structural and situational challenges. However, these challenges are also opportunities to innovate in a frugal way, involve the community, and adopt a customised approach that can be applied in the global practice of SSCs (Abad-Segura et al., 2020). The new global SSC environment will be more competitive and balanced, driven by greater investment, knowledge sharing, policy change, and inclusive innovation processes that empower institutions across all regions.

4 Gaps, challenges, and opportunities

This section integrates insights from the thematic findings and critically interprets the implications of smart sustainable campus (SSC) strategies across the five operational domains. It highlights interdependencies between sustainability dimensions, identifies strategic challenges, and suggests actionable pathways for institutions seeking systemic transformation.

4.1 Interpreting domain-level insights

The operational domains (waste, setting and infrastructure, energy, water, and mobility) demonstrate varying levels of maturity and innovation in SSC literature (Françoze et al., 2021). Energy management emerges as the most technologically advanced, benefiting from long-standing investments in smart grids and renewable energy (Zhou and Zheng, 2024). Here, real-time data integration and AI-driven optimisation are transforming demand forecasting, load balancing, and emissions tracking. Such innovation not only improves efficiency but also enhances institutional visibility in sustainability rankings (Ayyash and Salah, 2025). Setting and infrastructure, closely aligned with the physical transformation of campuses, reflect growing interest in green certifications and digital simulation tools (Santos, 2024). However, challenges persist in retrofitting legacy infrastructure, especially in public universities constrained by tight budgets and bureaucratic procurement systems. The use of digital twins and Building Information Modelling (BIM) points to a shift from reactive facility management to predictive, data-informed spatial governance (Kolokotsa et al., 2016). Water and waste management display moderate innovation, with significant progress in regions experiencing water stress or regulatory pressure (Wang et al., 2023). Smart meters, leak detection systems, and greywater recycling show promise but require coordinated maintenance, behavioural compliance, and infrastructure investment. In the case of waste, engagement campaigns and incentive structures significantly influence success, yet there remains a lack of standardised monitoring frameworks for waste diversion metrics across institutions (Shboul et al., 2023). Sustainable mobility is comparatively underdeveloped, often limited

to pilot initiatives or infrastructure support for cycling and EVs. Its progress is often hindered by institutional sprawl, student commuter patterns, and the absence of campus-wide low-carbon transport policies.

4.2 SSCs strategic integration: the need for systemic thinking

A key insight from this review is that isolated innovations are insufficient for achieving campus sustainability at scale. Institutions that demonstrated success across multiple domains did so by embedding sustainability into broader strategic plans, linking operational goals with institutional governance, funding structures, and performance evaluation metrics (Stamopoulos et al., 2024; Abad-Segura et al., 2020). Successful SSCs treat campus operations not as a siloed administrative function, but as a living laboratory that intersects with teaching, research, and community engagement (Sima et al., 2022). This aligns with the four strategic pillars of university sustainability identified in the literature: education, research, community partnerships, and operations. Integration also requires interdepartmental cooperation (Ribeiro et al., 2018). For instance, energy monitoring may involve facilities management, IT services, academic researchers, and sustainability officers. Without formalised coordination mechanisms, sustainability risks being compartmentalised or reduced to symbolic gestures.

4.3 SDG alignment and policy coherence

The operationalisation of SSC strategies offers tangible pathways for HEIs to contribute to global sustainability frameworks. The review finds the strongest alignment with:

- SDG 7 (Affordable and Clean Energy) through smart grids and renewable systems;
- SDG 11 (Sustainable Cities and Communities) via smart mobility and campus design;
- SDG 12 (Responsible Consumption and Production) through waste minimisation and material reuse;
- SDG 13 (Climate Action) across energy, infrastructure, and transport initiatives.

However, explicit mapping between SSC practices and SDG targets remains rare. Institutions often adopt sustainability branding without comprehensive impact assessments or integration into national climate and education policies (Sugandha et al., 2025). Moreover, the absence of global reporting standards for SSCs hinders benchmarking and knowledge exchange across institutions. International declarations such as the Talloires Declaration, Kyoto Declaration, and the UI Green Metric Rankings provide valuable frameworks but require further integration into SSC operational planning (Lan and Shizhu, 2025; Boiocchi et al., 2023; Rieckmann and Bormann, 2020). Only a minority of reviewed institutions link their campus strategies to these commitments in measurable ways.

This discussion demonstrates strong SSCs alignment with SDGs 7, 11, 12, and 13. Nevertheless, the inclusion of SDG 3 (Good Health and Well-Being) and SDG 4 (Quality Education) provides a more accurate representation of how SSCs can be viewed within the framework of global sustainability. Inclusive education and sustainability literacy (SDG 4) are encouraged in sustainable learning environments,

whereas the comfort, health, and productivity of occupants are ensured by a focus on indoor environmental quality (SDG 3). The campus is reinforced as a microcosm of sustainable urban systems through such integrative alignment, in which physical, digital, and social infrastructures converge to facilitate the full SDG agenda.

4.4 Constraints and risks

The review identified several recurring barriers:

- Financial limitations, especially in public and developing institutions, restrict smart infrastructure investments.
- Data privacy and cybersecurity concerns hinder IoT deployment and real-time monitoring.
- Resistance to change from staff or administrators delay digital and organisational transformation.
- Technological fragmentation, where different systems lack interoperability, undermines integrated decision-making.

Moreover, ethical issues arise in the increasing use of surveillance-based technologies, requiring stronger governance, transparency, and user consent mechanisms.

4.5 Opportunities for institutional innovation

Despite challenges, SSCs present powerful opportunities for HEIs to reinvent themselves as agents of sustainable development. This includes:

- Co-creation with students and faculty in designing, testing, and evaluating SSC solutions.
- Partnerships with industry, municipalities, and NGOs to scale campus innovations to city-wide sustainability agendas.
- Living lab models that embed real-world problem-solving into curricula and research.
- Open data platforms to democratise access to sustainability performance data, enhancing transparency and public accountability.

Institutions that strategically embrace these opportunities are likely to experience reputational gains, attract sustainability-conscious students, and influence policy innovation at national and international levels.

5 Conclusions and recommendations

5.1 Conclusion

This systematic literature review has critically examined global trends, frameworks, challenges, and opportunities associated with the operationalisation of Smart Sustainable Campuses (SSCs). By focusing on five core operational domains: energy management, setting and infrastructure, water management, waste management, and sustainable mobility, the review highlights the evolving landscape of sustainability in higher education institutions (HEIs). The findings emphasise a major shift from conventional campus operations toward sustainability-oriented, integrated, technology-enabled models. Smart technologies and predictive analysis help the energy and infrastructure

sectors to become the most mature areas of innovation. Other fields need more strategic funding and institutional coordination, though, notably sustainable mobility and waste. Moreover, the review exposes discrepancies in digital infrastructure, financial capacity, and policy alignment among HEIs in developed and developing countries, thereby exposing structural imbalances. While international declarations and ranking systems (e.g., the SDGs, the Talloires Declaration, and the UI GreenMetric) provide valuable frameworks, their translation into actionable campus strategies remains inconsistent.

The literature also showed an increasing focus on cross-cutting approaches fusing operations, education, research, and community involvement. Institutions that present SSCs as means for experiential learning and creativity, rather than as mere operational upgrades, are better suited to holistically promote sustainability goals. Still, obstacles persist, from ethical data utilisation and stakeholder opposition to financing limits and fragmented policy settings. These difficulties highlight the need for strong governance systems, context-sensitive planning, and interdisciplinary leadership to guide SSC transitions.

5.2 Recommendations

Based on the evidence synthesised in this review, several key recommendations are proposed to strengthen SSC implementation:

- i **Develop Integrated Sustainability Strategies**
HEIs should move beyond isolated interventions by adopting campus-wide sustainability frameworks that align institutional missions with operational performance metrics, SDG targets, and international sustainability declarations.
- ii **Prioritise Technological Interoperability**
Institutions should invest in scalable, interoperable digital platforms that unify data across all operational domains. This enables effective decision-making, predictive analytics, and seamless monitoring of campus sustainability performance.
- iii **Promote Inclusive Stakeholder Engagement**
SSC success depends on the involvement of all campus actors, students, faculty, administrative staff, and external partners. Participatory design processes, sustainability curricula, and co-creation initiatives should be institutionalised.
- iv **Strengthen Capacity in Developing Contexts**
Policymakers and donors should support HEIs in the Global South by providing access to financial mechanisms, capacity-building programs, and low-cost smart technologies. Regional collaboration platforms could facilitate learning and policy alignment in the Global South.
- v **Institutionalise Ethical Governance**
As campuses become data-rich environments, HEIs must establish transparent data governance protocols that ensure ethical use of IoT, AI, and surveillance technologies, in accordance with privacy rights and informed consent principles.
- vi **Benchmark and Report Progress**
Institutions should adopt standardised SSC performance indicators, potentially aligned with SDGs and UI GreenMetrics, to

benchmark their progress and enable comparative learning across global institutions.

vii Advance Research on Underserved Domains

Further empirical work is needed in waste management, sustainable mobility, and social behaviour change strategies, especially in underrepresented regions. Interdisciplinary research should explore long-term impacts of SSCs on institutional resilience, academic culture, and sustainability literacy.

Author contributions

AE: Data curation, Methodology, Software, Conceptualization, Writing – review & editing, Investigation, Validation, Resources, Formal analysis, Writing – original draft, Visualization, Project administration. EE: Visualization, Data curation, Methodology, Validation, Conceptualization, Project administration, Supervision, Resources, Software, Writing – original draft, Formal analysis, Writing – review & editing. DB: Data curation, Validation, Methodology, Conceptualization, Project administration, Supervision, Writing – original draft, Writing – review & editing, Formal analysis, Visualization.

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Supplementary material

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References

- Abad-Segura, E., González-Zamar, M.-D., Infante-Moro, J. C., and Ruipérez García, G. (2020). Sustainable management of digital transformation in higher education: global research trends. *Sustainability* 12:2107. doi: 10.3390/su12052107
- Abo-Khalil, A. G. (2024). Integrating sustainability into higher education challenges and opportunities for universities worldwide. *Heliyon* 10, e29946–e29946. doi: 10.1016/j.heliyon.2024.e29946
- Abu-Rayash, A., and Dincer, I. (2023). Development of an integrated sustainability model for resilient cities featuring energy, environmental, social, governance and pandemic domains. *Sustain. Cities Soc.* 92:104439. doi: 10.1016/j.scs.2023.104439
- Adenle, Y. A., Chan, E. H. W., Sun, Y., and Chau, C. K. (2021). Assessing the relative importance of sustainability indicators for smart campuses: a case of higher education institutions in Nigeria. *Environ. Sustain. Indic.* 9:100092. doi: 10.1016/j.indic.2020.100092
- Adeyemi, O. J., Popoola, S. I., Atayero, A. A., Afolayan, D. G., Ariyo, M., and Adetiba, E. (2018). Exploration of daily internet data traffic generated in a smart university campus. *Data Brief* 20, 30–52. doi: 10.1016/j.dib.2018.07.039
- Agarwal, S. M. (2023). Go-Brown, go-green and smart initiatives implemented by the University of Delhi for environmental sustainability towards futuristic smart universities: observational study. *Heliyon* 9:e13909. doi: 10.1016/j.heliyon.2023.e13909
- Agrawal, S., Oza, P., Kakkar, R., Sudeep Tanwar, V., Jatin, U., and Singh, A. (2024). Analysis and recommendation system-based on PRISMA checklist to write systematic review. *Assess. Writing* 61, 100866–100866. doi: 10.1016/j.asw.2024.100866
- Ahlborg, H., Ruiz-Mercado, I., Molander, S., and Masera, O. (2019). Bringing technology into social-ecological systems research—motivations for a socio-technical-ecological systems approach. *Sustainability* 11:2009. doi: 10.3390/su11072009
- Ajaj, R., Buniya, M. K., Wuni, I. Y., and Yousif, O. S. (2025). A structural equation model of the critical success factors for sustainable smart cities: a case study of Abu Dhabi. *J. Urban Manag.* 14, 843–855. doi: 10.1016/j.jum.2025.02.008
- Ajiboye, A. A., Popoola, S. I., Adewuyi, O. B., Atayero, A. A., and Adebisi, B. (2022). Data-driven optimal planning for hybrid renewable energy system management in smart campus: a case study. *Sustain Energy Technol Assess* 52:102189. doi: 10.1016/j.seta.2022.102189
- Akbar, H. A., Faturrahman, M. R., and Sidharta, S. (2023). Guidance in designing a smart campus: a systematic literature review. *Proc. Comput. Sci.* 227, 83–91. doi: 10.1016/j.procs.2023.10.505
- Alrashed, S. (2020). Key performance indicators for smart campus and microgrid. *Sustain. Cities Soc.* 60:102264. doi: 10.1016/j.scs.2020.102264

- Alshuwaikhat, H. M., Aina, Y. A., and Binsaedan, L. (2022). Analysis of the implementation of urban computing in smart cities: a framework for the transformation of Saudi cities. *Heliyon* 8:e11138. doi: 10.1016/j.heliyon.2022.e11138
- Amaral, A. R., Rodrigues, E., Gaspar, A. R., and Gomes, Á. (2020). A review of empirical data of sustainability initiatives in university campus operations. *J. Clean. Prod.* 250:119558. doi: 10.1016/j.jclepro.2019.119558
- Amr, E., Mostafa, N. A., and Matsushita, Y. (2021). Toward a smart and sustainable campus: future vision, opportunities, and challenges. *Adv. Sci. Technol. Innov.* 2021, 233–242. doi: 10.1007/978-3-030-63567-1_20
- Anthony, B. (2020). Green campus paradigms for sustainability attainment in higher education institutions – a comparative study. *J. Sci. Technol. Policy Manag.* 12, 117–148. doi: 10.1108/jstpm-02-2019-0008
- Atay, S., Müftüoğlu, C. T., Gülmez, N., and Şahin, M. (2025). Society 5.0 and human-centered technology: redefining talent management in the digital age. *Sustain. Futures* 9:100733. doi: 10.1016/j.sfr.2025.100733
- Ayyash, M. M., and Salah, O. H. (2025). AI adoption in higher education: advancing sustainable energy management in Palestinian universities. *J. Open Innov. Technol. Mark. Complex.* 11:100534. doi: 10.1016/j.oiotmc.2025.100534
- Azzali, S., and Sabour, E. A. (2018). A framework for improving sustainable mobility in higher education campuses: the case study of Qatar University. *Case Stud. Transp. Policy* 6, 603–612. doi: 10.1016/j.cstp.2018.07.010
- Basheer, N., Ahmed, V., Bahroun, Z., and Anane, C. (2025). Sustainability assessment in higher education institutions: exploring indicators, stakeholder perceptions, and implementation challenges. *Discov. Sustain.* 6:116. doi: 10.1007/s43621-025-01116-w
- Bashir, H. A., Zehra, C. A., Khaled, O., and Imad, A. (2023). An approach for analyzing and visualising the relationships among key performance indicators for creating sustainable campuses in higher education institutions. *Environ. Sustain. Indic.* 19:100267. doi: 10.1016/j.indic.2023.100267
- Batal, M., Daissouli, A., Sanaa, E. F., and Lbath, A. (2024). Towards a novel approach based on machine learning to assess environmental suitability in smart campuses. *Proc. Comput. Sci.* 236, 348–355. doi: 10.1016/j.procs.2024.05.040
- Boiocchi, R., Ragazzi, M., Torretta, V., and Rada, E. C. (2023). Critical analysis of the green metric world university ranking system: the issue of comparability. *Sustainability* 15:1343. doi: 10.3390/su15021343
- Chagnon-Lessard, N., Gosselin, L., Barnabe, S., Bello-Ochende, T., Fendt, S., Goers, S., et al. (2021). Smart campuses: extensive review of the last decade of research and current challenges. *IEEE Access* 9, 124200–124234. doi: 10.1109/access.2021.3109516
- Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., and Sovacool, B. (2018). Integrating techno-economic, socio-technical and political perspectives on national energy transitions: a meta-theoretical framework. *Energy Res. Soc. Sci.* 37, 175–190. doi: 10.1016/j.erss.2017.09.015
- Clement, J., Ruysschaert, B., and Crutzen, N. (2023). Smart city strategies – a driver for the localization of the sustainable development goals? *Ecol. Econ.* 213:107941. doi: 10.1016/j.ecolecon.2023.107941
- Cunha, F., Dinis-Carvalho, J., and Sousa, R. M. (2024). Assessment of performance measurement systems' ability to mitigate or eliminate typical barriers compromising organisational sustainability. *Sustainability* 16, 2173–2173. doi: 10.3390/su16052173
- Da Costa, M. M. (2025). The management of higher education institutions in Portugal from a sustainable perspective. *Proc. Comput. Sci.* 256, 706–717. doi: 10.1016/j.procs.2025.02.170
- Das, D., Lim, N. D., and Aravind, P. (2022). Developing a smart and sustainable campus in Singapore. *Sustainability* 14:14472. doi: 10.3390/su142114472
- Dawodu, A., Dai, H., Zou, T., Zhou, H., Lian, W., Oladejo, J., et al. (2022). Campus sustainability research: indicators and dimensions to consider for the design and assessment of a sustainable campus. *Heliyon* 8:e11864. doi: 10.1016/j.heliyon.2022.e11864
- de Puppim Oliveira, J. A., Bellezoni, R. A., Shih, W., and Bayulken, B. (2022). Innovations in urban green and blue infrastructure: tackling local and global challenges in cities. *J. Clean. Prod.* 362:132355. doi: 10.1016/j.jclepro.2022.132355
- Doaa, G., and Davies, D. (2025). The rise of sustainable development goals in higher education institutions. *Perspect. Policy Pract. High. Educ.* 2025, 1–8. doi: 10.1080/13603108.2025.2528053
- Dominguez-Bolaño, T., Barral, V., Escudero, C. J., and García-Naya, J. A. (2024). An IoT system for a smart campus: challenges and solutions illustrated over several real-world use cases. *Internet Things* 25:101099. doi: 10.1016/j.iot.2024.101099
- Duanmu, J. L., and Chai, W. K. (2025). Modelling innovation adoption spreading in complex networks. *Appl. Netw. Sci.* 10:69. doi: 10.1007/s41109-025-00698-8
- Dzhuguryan, T., and Deja, A. (2021). Sustainable waste management for a city multifloor manufacturing cluster: a framework for designing a smart supply chain. *Sustainability* 13:1540. doi: 10.3390/su13031540
- Elkington, J. (1997). Partnerships from cannibals with forks: the triple bottom line of 21st-century business. *Environ. Qual. Manag.* 8, 37–51. doi: 10.1002/tqem.3310080106
- Esfilar, R., Bagheri, M., and Golestani, B. (2021). Technoeconomic feasibility review of hybrid waste to energy system in the campus: a case study for the University of Victoria. *Renew. Sust. Energy Rev.* 146:111190. doi: 10.1016/j.rser.2021.111190
- Ferraris, A., Belyaeva, Z., and Bresciani, S. (2020). The role of universities in the Smart City innovation: multistakeholder integration and engagement perspectives. *J. Bus. Res.* 119:10. doi: 10.1016/j.jbusres.2018.12.010
- Françoze, R., Paucar-Caceres, A., and Belderrain, M. C. N. (2021). Combining value-focused thinking and soft systems methodology: a systemic framework to structure the planning process at a special educational needs school in Brazil. *J. Oper. Res. Soc.* 73, 994–1013. doi: 10.1080/01605682.2021.1880298
- García-Monge, M., Zalba, B., Casas, R., Cano, E., Guillén-Lambea, S., López-Mesa, B., et al. (2023). Is IoT monitoring key to improve building energy efficiency? Case study of a smart campus in Spain. *Energ. Buildings* 285:112882. doi: 10.1016/j.enbuild.2023.112882
- González-García, A., Aguado, M., Solascasas, P., Palomo, I., González, J. A., García-Llorente, M., et al. (2023). Co-producing an ecosystem services-based plan for sustainable university campuses. *Landsc. Urban Plan.* 230:104630. doi: 10.1016/j.landurbplan.2022.104630
- Gu, Q., Sing, M. C. P., Jefferies, M., and Kanjanabootra, S. (2025). Bridging the gap between smart cities and sustainability: current practices and future trends. *Cities* 159:105799. doi: 10.1016/j.cities.2025.105799
- Hariram, N. P., Mekha, K. B., Suganthan, V., and Sudhakar, K. (2023). Sustainability: an integrated socio-economic-environmental model to address sustainable development and sustainability. *Sustainability* 15:10682. doi: 10.3390/su151310682
- Herth, A., Verburg, R., and Blok, K. (2024). How can campus living labs thrive to reach sustainable solutions? *Clean. Product. Lett.* 8:100078. doi: 10.1016/j.cpl.2024.100078
- Hiltunen, P., Volkova, A., Eduard, L., Kertu, L., and Sanna, S. (2022). Transition towards university campus carbon neutrality by connecting to city district heating network. *Energy Rep.* 8, 9493–9505. doi: 10.1016/j.egy.2022.07.055
- Horan, W., and O'Regan, B. (2021). Developing a practical framework of sustainability indicators relevant to all higher education institutions to enable meaningful international rankings. *Sustainability* 13:629. doi: 10.3390/su13020629
- Hussain, S., and Sheikh, H. A. (2023). Sustainability assessment by green building rating systems: a comparative analysis of LEED, BREEAM and CASBEE on a case study. *Int. J. Multidiscip. Res.* 5:29. doi: 10.36948/ijfmr.2023.v05i06.8935
- Ivars-Baidal, J. A., Celdrán-Bernabeu, M. A., Femenia-Serra, F., Perles-Ribes, J. F., and Vera-Rebollo, J. E. (2023). Smart city and smart destination planning: examining instruments and perceived impacts in Spain. *Cities* 137:104266. doi: 10.1016/j.cities.2023.104266
- Jawad, A., Hasan, M. S., Faruqui, M. F. I., and Masood, N. A. (2023). Small-scale floating photovoltaic systems in university campus: a pathway to achieving SDG 7 goals in Bangladesh. *Energy Convers. Manag.* 297:117722. doi: 10.1016/j.enconman.2023.117722
- Jiang, Q., and Kurnitski, J. (2023). Performance based core sustainability metrics for university campuses developing towards climate neutrality: a robust PICSOU framework. *Sustain. Cities Soc.* 97:104723. doi: 10.1016/j.scs.2023.104723
- Jiao, Y., Kang, H., and Sun, H. (2024). An intelligent landscaping framework for net-zero energy smart cities: a green infrastructure approach. *Sustain Energy Technol Assess* 64, 103665–103665. doi: 10.1016/j.seta.2024.103665
- Kaiser, Z. R. M. A., and Deb, A. (2025). Sustainable smart city and sustainable development goals (SDGs): a review. *Reg. Sustain.* 6:100193. doi: 10.1016/j.regsus.2025.100193
- Karale, A. (2021). The challenges of IoT addressing security, ethics, privacy and laws. *Internet Things* 15:100420. doi: 10.1016/j.iot.2021.100420
- Kim, H., Choi, H., Kang, H., An, J., Yeom, S., and Hong, T. (2021). A systematic review of the smart energy conservation system: from smart homes to sustainable smart cities. *Renew. Sust. Energy Rev.* 140:110755. doi: 10.1016/j.rser.2021.110755
- Kolokotsa, D., Gobakis, K., Papantoniou, S., Georagatou, C., Kampelis, N., Kalaitzakis, K., et al. (2016). Development of a web based energy management system for university campuses: the CAMP-IT platform. *Energ. Buildings* 123, 119–135. doi: 10.1016/j.enbuild.2016.04.038
- Kourgozou, V., Commin, A., Dowson, M., Rovas, D., and Mumovic, D. (2021). Scalable pathways to net zero carbon in the UK higher education sector: a systematic review of smart energy systems in university campuses. *Renew. Sust. Energy Rev.* 147:111234. doi: 10.1016/j.rser.2021.111234
- Lan, O., and Shizhu, L. (2025). Educational building renovation for sustainability: exploring key factors and pathways. *Alex. Eng. J.* 120, 614–626. doi: 10.1016/j.aej.2025.02.015
- Leal, F. W., Frankenberger, F., Salvia, A. L., Azeiteiro, U., Alves, F., Castro, P., et al. (2021). A framework for the implementation of the sustainable development goals in university programmes. *J. Clean. Prod.* 299:126915. doi: 10.1016/j.jclepro.2021.126915
- Leticia, F. H., Walquiria, N. S., Bruno, H. D., and Leonardo, W. O. (2023). Optimal siting and sizing of distributed energy resources in a smart campus. *Electr. Power Syst. Res.* 217:109095. doi: 10.1016/j.epr.2022.109095
- Lim, C. K., Haufiku, M. S., Tan, K. L., Farid Ahmed, M., and Ng, T. F. (2022). Systematic review of education sustainable development in higher education institutions. *Sustainability* 14:13241. doi: 10.3390/su142013241
- Liu, T., Guan, X., Wang, Z., Qin, T., Sun, R., and Wang, Y. (2024). Optimising green supply chain circular economy in smart cities with integrated machine learning technology. *Heliyon* 10, e29825–e29825. doi: 10.1016/j.heliyon.2024.e29825
- Liu, Q., and Ren, J. (2020). Research on the building energy efficiency design strategy of Chinese universities based on green performance analysis. *Energ. Buildings* 224:110242. doi: 10.1016/j.enbuild.2020.110242

- Liu, B. W., Wang, M. H., Chen, T. L., Tseng, P. C., Sun, Y., Chiang, A., et al. (2020). Establishment and implementation of green infrastructure practice for healthy watershed management: challenges and perspectives. *Water Energy Nexus* 3, 186–197. doi: 10.1016/j.wen.2020.05.003
- Mahmoud, A. S., Hassanain, M. A., and Adel, A. (2024). Evolving trends and innovations in facilities management within higher education institutions. *Buildings* 14, 3759–3759. doi: 10.3390/buildings14123759
- Mai, T., Bui, T., and Pham, B. T. (2024). The role of higher education in achieving sustainable development goals: an evaluation of motivation and capacity of Vietnamese institutions. *Int. J. Manag. Educ.* 22, 101088–101088. doi: 10.1016/j.ijme.2024.101088
- Makhoul, N. (2022). Review of data quality indicators and metrics, and suggestions for indicators and metrics for structural health monitoring. *Adv. Bridge Eng.* 3:68. doi: 10.1186/s43251-022-00068-9
- Malagnino, A., Montanaro, T., Lazoi, M., Sergi, I., Corallo, A., and Patrono, L. (2021). Building information modelling and internet of things integration for smart and sustainable environments: a review. *J. Clean. Prod.* 312:127716. doi: 10.1016/j.jclepro.2021.127716
- Marín-González, F., Moganadas, S. R., Paredes-Chacín, A. J., Yeo, S. F., and Subramaniam, S. (2022). Sustainable local development: consolidated framework for cross-sectoral cooperation via a systematic approach. *Sustainability* 14:6601. doi: 10.3390/su14116601
- Martínez, I., Zalba, B., Trillo-Lado, R., Blanco, T., Cambra, D., and Casas, R. (2021). Internet of things (IoT) as sustainable development goals (SDG) enabling technology towards smart readiness indicators (SRI) for university buildings. *Sustainability* 13:7647. doi: 10.3390/su13147647
- Mihic, M. M., Shevchenko, S., Gligorijević, E. D., and Petrović, D. Č. (2019). Towards strategic corporate social responsibility approach in international projects—review of south-south cooperation: a case study of Chinese projects in Angola. *Sustainability* 11:2784. doi: 10.3390/su11102784
- Mohammed, A. M. S., Ukai, T., and Hall, M. (2022). Towards a sustainable campus-city relationship: a systematic review of the literature. *Reg. Sustain.* 3, 53–67. doi: 10.1016/j.regus.2022.03.004
- Muqet, H. A., Javed, H., Akhter, M. N., Shahzad, M., Munir, H. M., Nadeem, M. U., et al. (2022). Sustainable solutions for advanced energy management system of campus microgrids: model opportunities and future challenges. *Sensors* 22:2345. doi: 10.3390/s22062345
- Negri, M., Cagno, E., Colicchia, C., and Sarkis, J. (2021). Integrating sustainability and resilience in the supply chain: a systematic literature review and a research agenda. *Bus. Strat. Environ.* 30, 2858–2886. doi: 10.1002/bse.2776
- Nkem, E. A., Kesi-Ayeba, K. D., Olakunle, O. S., and Oluwafemi, J. (2019). Study of energy efficient building design techniques: Covenant University health Centre. *J. Phys. Conf. Ser.* 1378:032037. doi: 10.1088/1742-6596/1378/3/032037
- O’Dea, R. E., Lagisz, M., Jennions, M. D., Koricheva, J., Noble, D. W. A., Parker, T. H., et al. (2021). Preferred reporting items for systematic reviews and meta-analyses in ecology and evolutionary biology: a PRISMA extension. *Biol. Rev.* 96, 1695–1722. doi: 10.1111/brv.12721
- Okeniyi, J. O., Atayero, A. A., Popoola, S. I., Okeniyi, E. T., and Alalade, G. M. (2018). Smart campus: data on energy generation costs from distributed generation systems of electrical energy in a Nigerian university. *Data Brief* 17, 1082–1090. doi: 10.1016/j.dib.2018.02.022
- Okoro, E. E., Okafor, I. S., Igwilo, K. C., Orodu, K. B., and Mamudu, A. O. (2020). Sustainable biogas production from waste in potential states in Nigeria – alternative source of energy. *J. Contemp. Afr. Stud.* 38, 627–643. doi: 10.1080/02589001.2020.1825650
- Olawumi, T. O., Chan, D. W. M., Saka, A. B., Ekundayo, D., and Odeh, A. O. (2023). Are there any gains in green-tech adoption? Unearthing the beneficial outcomes of smart-sustainable practices in Nigeria and Hong Kong built environment. *J. Clean. Prod.* 410:137280. doi: 10.1016/j.jclepro.2023.137280
- Oliveira, M. C., and Proença, J. (2025). Sustainable campus operations in higher education institutions: a systematic literature review. *Sustainability* 17:607. doi: 10.3390/su17020607
- Olukanni, D., Aipoh, A., and Kalabo, I. (2018). Recycling and reuse technology: waste to wealth initiative in a private tertiary institution, Nigeria. *Recycling* 3:44. doi: 10.3390/recycling3030044
- Oyadeyi, O. A., and Oyadeyi, O. O. (2025). Towards inclusive and sustainable strategies in smart cities: a comparative analysis of Zurich, Oslo, and Copenhagen. *Res. Glob.* 10:100271. doi: 10.1016/j.resglo.2025.100271
- Oyedepo, S. O., Anifowose, E. G., Obembe, E. O., and Khanmohamadi, S. (2021). “Energy-saving strategies on university campus buildings: Covenant University as case study” in *Energy services fundamentals and financing*, 131–154.
- Oyedepo, S. O., Dirisu, J. O., Efemwenkiele, U. K., Fayomi, O. S. I., and Essien, E. E. (2019). Comprehending the energy consumption pattern of occupancy of an academic structure. *J. Phys.* 1378:022027. doi: 10.1088/1742-6596/1378/2/022027
- Pacini, A., Brüggemann, M., Flottmann, M., Großschedl, J., and Schlüter, K. (2025). Sustainability education through green facades: effects of a short-term intervention on environmental knowledge, attitude, and practices. *Sustainability* 17:2609. doi: 10.3390/su17062609
- Pan, X., Khan, A. M., Eldin, S. M., Aslam, F., Rehman, S. K. U., and Jameel, M. (2023). BIM adoption in sustainability, energy modelling and implementing using ISO 19650: a review. *Ain Shams Eng. J.* 15:102252. doi: 10.1016/j.asej.2023.102252
- Panaite, F. A., Rus, C., Leba, M., Andreea Cristina, I., and Windisch, M. (2024). Enhancing air-quality predictions on university campuses: a machine-learning approach to PM2.5 forecasting at the University of Petroșani. *Sustainability* 16, 7854–7854. doi: 10.3390/su16177854
- Pandiyan, S., Saravanan, R., Kannadasan, S., Krishnaveni, Alsharif, M. H., and Kim, M.-K. (2024). A comprehensive review of advancements in green IoT for smart grids: paving the path to sustainability. *Energy Rep.* 11, 5504–5531. doi: 10.1016/j.egy.2024.05.021
- Pankaj, B., Rani, S., and Khang, A. (2024). AI-driven digital twin and resource optimization in industry 4.0 ecosystem. Florida: CRC Press.
- Papantoniou, P., Yannis, G., Vlahogianni, E., Attard, M., Regattieri, A., Piana, F., et al. (2020). Developing a sustainable mobility action plan for university campuses. *Transp. Res. Procedia* 48, 1908–1917. doi: 10.1016/j.trpro.2020.08.223
- Pereira, L., Asrar, G. R., Bhargava, R., Fisher, L. H., Hsu, A., Jabbour, J., et al. (2021). Grounding global environmental assessments through bottom-up futures based on local practices and perspectives. *Sustainability Science* 16, 1907–1922. doi: 10.1007/s11625-021-01013-x
- Polin, K., Yigitcanlar, T., Limb, M., and Washington, T. (2023). The making of smart campus: a review and conceptual framework. *Buildings* 13:891. doi: 10.3390/buildings13040891
- Ramírez, O., Hernández-Cuellar, B., and de la Rosa, J. D. (2023). Air quality monitoring on university campuses as a crucial component to move toward sustainable campuses: an overview. *Urban Clim.* 52:101694. doi: 10.1016/j.uclim.2023.101694
- Ramos, T. B., Caeiro, S., van Hoof, B., Lozano, R., Huisingh, D., and Ceulemans, K. (2015). Experiences from the implementation of sustainable development in higher education institutions: environmental management for sustainable universities. *J. Clean. Prod.* 106, 3–10. doi: 10.1016/j.jclepro.2015.05.110
- Rane, N. (2023). Integrating leading-edge artificial intelligence (AI), internet of things (IoT), and big data Technologies for Smart and Sustainable Architecture, engineering and construction (AEC) industry: challenges and future directions. *Soc. Sci. Res. Netw.* 3, 73–95. doi: 10.51483/IJDSBDA.3.2.2023.73-95
- Rehman, S., Abdul Baseer, M., Alhems, L. M., and Alsulaiman, F. A. (2024). Smart car parks with EV charging for academic campus. *Clean. Energy Syst.* 8:100121. doi: 10.1016/j.cles.2024.100121
- Reihaneh, A., and Marzieh, F. (2023). Strategies towards reducing carbon emission in university campuses: a comprehensive review of both global and local scales. *J. Build. Eng.* 76:107183. doi: 10.1016/j.job.2023.107183
- Reimers, F. M. (2024). The sustainable development goals and education, achievements and opportunities. *Int. J. Educ. Dev.* 104, 102965–102965. doi: 10.1016/j.ijedudev.2023.102965
- Rey-Hernández, J. M., Rey-Martínez, F. J., Yousif, C., and Krawczyk, D. (2023). Assessing the performance of a renewable district heating system to achieve nearly zero-energy status in renovated university campuses: a case study for Spain. *Energy Convers. Manag.* 292:117439. doi: 10.1016/j.enconman.2023.117439
- Ribeiro, J. M., Bocasanta, S. L., Ávila, B. O., Magtoto, M., Jonck, A. V., Gabriel, G. M., et al. (2018). The adoption of strategies for sustainable cities: a comparative study between Seattle and Florianopolis legislation for energy and water efficiency in buildings. *J. Clean. Prod.* 197, 366–378. doi: 10.1016/j.jclepro.2018.06.176
- Ribeiro, P., Fonseca, F., and Meireles, T. (2020). Sustainable mobility patterns to university campuses: evaluation and constraints. *Case Stud. Transp. Policy* 8:5. doi: 10.1016/j.cstp.2020.02.005
- Ribeiro, J. M., Hoekesfeld, L., Dal Magro, C. B., Favretto, J., Barichello, R., Lenzi, F. C., et al. (2021). Green campus initiatives as sustainable development dissemination at higher education institutions: students’ perceptions. *J. Clean. Prod.* 312:127671. doi: 10.1016/j.jclepro.2021.127671
- Rieckmann, M., and Bormann, I. (2020). *Higher education institutions and sustainable development*. Switzerland: MDPI eBooks.
- Rodgers, M. D. (2021). Pathways to eliminate carbon emissions via renewable energy investments at higher education institutions. *Electr. J.* 34:106952. doi: 10.1016/j.tej.2021.106952
- Rodrigues, M., and Franco, M. (2021). The role of citizens and transformation of energy, water, and waste infrastructure for an intelligent, sustainable environment in cities. *Smart Sustain. Built Environ.* 12, 385–406. doi: 10.1108/sasbe-06-2021-0094
- Rodríguez, B. M., Alcaide Muñoz, L., and Alcaide Muñoz, C. (2023). Identifying patterns in smart initiatives’ planning in smart cities. An empirical analysis in Spanish smart cities. *Technol. Forecast. Soc. Change* 196:122781. doi: 10.1016/j.techfore.2023.122781
- Rodríguez-Guerreiro, M. J., Torrijos, V., and Soto, M. (2024). A review of waste management in higher education institutions: the road to zero waste and sustainability. *Environments* 11:293. doi: 10.3390/environments11120293
- Rogers, E. M. (2003). *Diffusion of innovations*. 5th Edn. New York: Simon and Schuster.

- Saha, A. K., Al-Shaer, H., Dixon, R., and Demirag, I. (2020). Determinants of carbon emission disclosures and UN sustainable development goals: the case of UK higher education institutions. *Aust. Account. Rev.* 31:12324. doi: 10.1111/auar.12324
- Sangita, M. S., and Sakharle, D. (2022). Design of green roof for an energy efficient university campus. *Mater Today Proc.* 65, 1546–1550. doi: 10.1016/j.matpr.2022.04.505
- Santos, E.A. 2024. Smart and sustainable mobility: New trends, business models, technologies and cases - A study strategy. Riunet.upv.es. Available online at: <http://hdl.handle.net/10251/212411> (Accessed August 8, 2025).
- Sen, G., Chau, H. W., Tariq, M. A., Muttill, N., and Ng, A. M. (2021). Achieving sustainability and carbon neutrality in higher education institutions: a review. *Sustainability* 14:222. doi: 10.3390/su14010222
- Serafini, P.G., Moura, J.M.de, Almeida, M.R.de, and Rezende, J.F.D.de 2022 Sustainable development goals in higher education institutions: a systematic literature review *J. Clean. Prod.* 370:133473 doi: 10.1016/j.jclepro.2022.133473
- Shao, J., and Min, B. (2024). Sustainable development strategies for smart cities: review and development framework. *Cities* 158:105663. doi: 10.1016/j.cities.2024.105663
- Sharifi, A., Allam, Z., Bibri, S. E., and Khavarian-Garmsir, A. R. (2024). Smart cities and sustainable development goals (SDGs): a systematic literature review of co-benefits and trade-offs. *Cities* 146:104659. doi: 10.1016/j.cities.2023.104659
- Shboul, B., Koh, S. C. L., Veneti, C., Herghelegiu, A. I., Zinca, A. E., and Pourkashanian, M. (2023). Evaluating sustainable development practices in a zero-carbon university campus: a pre and post-COVID-19 pandemic recovery study. *Sci. Total Environ.* 896:165178. doi: 10.1016/j.scitotenv.2023.165178
- Shu, J., and Tian, L. (2024). Conceptualising and comparing world-class universities' contributions to global sustainability: pathways, priorities and potential indicators. *Int. J. Educ. Dev.* 110:103138. doi: 10.1016/j.ijedudev.2024.103138
- Silva-da-Nóbrega, P. I., Chim-Miki, A. F., and Castillo-Palacio, M. (2022). A smart campus framework: challenges and opportunities for education based on the sustainable development goals. *Sustainability* 14:9640. doi: 10.3390/su14159640
- Sima, M., Grigorescu, I., Bălăteanu, D., and Nikolova, M. (2022). A comparative analysis of campus greening practices at universities in Romania and Bulgaria: sharing the same challenges? *J. Clean. Prod.* 373:133822. doi: 10.1016/j.jclepro.2022.133822
- Sony, M., and Naik, S. (2020). Industry 4.0 integration with socio-technical systems theory: a systematic review and proposed theoretical model. *Technol. Soc.* 61, 1–11. doi: 10.1016/j.techsoc.2020.101248
- Stamopoulos, D., Dimas, P., Siokas, G., and Siokas, E. (2024). Getting smart or going green? Quantifying the Smart City industry's economic impact and potential for sustainable growth. *Cities* 144:104612. doi: 10.1016/j.cities.2023.104612
- Stuckrath, C., Rosales-Carreón, J., and Worrell, E. (2025). Conceptualisation of campus living labs for the sustainability transition: an integrative literature review. *Environ. Dev.* 54:101143. doi: 10.1016/j.envdev.2025.101143
- Sugandha, Freestone, R., and Favaro, P. (2025). Social sustainability, smart cities and the global south: learning from the Indian experience. *Cities* 165:106149. doi: 10.1016/j.cities.2025.106149
- Tan, S. Y., and Taeihagh, A. (2020). Smart city governance in developing countries: a systematic literature review. *Sustainability* 12:899. doi: 10.3390/su12030899
- Urbano, V. M., Arena, M., Azzone, G., and Mayeres, M. (2025). Sustainable development in higher education: an in-depth analysis of Times Higher Education impact rankings. *J. Clean. Prod.* 501:145302. doi: 10.1016/j.jclepro.2025.145302
- Verdejo, Á., Espinilla, M., López, J. L., and Melguizo, F. J. (2022). Assessment of sustainable development objectives in smart labs: technology and sustainability at the service of society. *Sustain. Cities Soc.* 77:103559. doi: 10.1016/j.scs.2021.103559
- Wang, H., Chen, X., Jia, F., and Cheng, X. (2023). Digital twin-supported smart city: status, challenges and future research directions. *Expert Syst. Appl.* 217:119531. doi: 10.1016/j.eswa.2023.119531
- Weil, C., Bibri, S. E., Longchamp, R., Golay, F., and Alahi, A. (2023). Urban digital twin challenges: a systematic review and perspectives for sustainable smart cities. *Sustain. Cities Soc.* 99:104862. doi: 10.1016/j.scs.2023.104862
- Wen, J., Hussain, H., Jiang, R., and Waheed, J. (2023). Overcoming the digital divide with ICT diffusion: multivariate and spatial analysis at China's provincial level. *SAGE Open* 13, 215824402311593–215824402311593. doi: 10.1177/21582440231159323
- Xie, S., Luo, N., and Masaru, Y. (2023). Data governance for smart cities in China: the case of Shenzhen. *Policy Des. Pract.* 7, 1–21. doi: 10.1080/25741292.2023.2297445
- Yan, Z., Sun, Z., Shi, R., and Zhao, M. (2023). Smart city and green development: empirical evidence from the perspective of green technological innovation. *Technol. Forecast. Soc. Change* 191:122507. doi: 10.1016/j.techfore.2023.122507
- Zaballos, A., Briones, A., Massa, A., Centelles, P., and Caballero, V. (2020). A smart campus' digital twin for sustainable comfort monitoring. *Sustainability* 12:9196. doi: 10.3390/su12219196
- Zainullah, S., Massoud, D., and Fida, M. (2024). Optimising hybrid PV/wind and grid systems for sustainable energy solutions at the university campus: economic, environmental, and sensitivity analysis. *Energy Conv. Manag.* 10:100691. doi: 10.1016/j.ecmx.2024.100691
- Žalėnienė, I., and Pereira, P. (2021). Higher education for sustainability: a global perspective. *Geogr. Sustain.* 2, 99–106. doi: 10.1016/j.geosus.2021.05.001
- Zhou, Y., and Zheng, S. (2024). A co-simulated material-component-system-district framework for climate-adaptation and sustainability transition. *Renew. Sust. Energ. Rev.* 192:114184. doi: 10.1016/j.rser.2023.114184
- Zyoud, S., and Zyoud, A. H. (2025). Advancing sustainable cities and communities with internet of things: global insights, trends, and research priorities for SDG 11. *Results Eng.* 26:104917. doi: 10.1016/j.rineng.2025.104917