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Strategies and challenges for green campuses

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The global environmental and ecological climate crisis necessitates urgent mitigation and adaptation measures, with Higher Education Institutions (HEIs) playing a crucial role in driving the transition toward a sustainable future. This paper examines the dual approach HEIs can adopt to foster sustainability: educating future generations and implementing green campus initiatives that can serve as models for the broader community. This review synthesizes existing research and case studies, identifies key areas for sustainability efforts within HEIs and analyzes the barriers and potential solutions for implementing sustainable practices on campuses. The broad range of areas include energy efficiency and renewable production, emissions mitigation, water and waste management, sustainable buildings and laboratories, and eco-friendly landscaping. The synthesis of findings revealed that HEIs can function as microcosms of sustainable urban environments, showcasing efficient resource management and infrastructure enhancement. Additionally, it highlighted the various actions HEIs should take to achieve campus sustainability. The major actions include establishing a dedicated Sustainability Office to coordinate efforts and set measurable goals; Implementing environmental initiatives (such as energy conservation and waste reduction); Engaging all campus stakeholders through education and participation in sustainability programs; Adopting standardized practices for resource management; Securing strong leadership support and funding; Fostering collaboration and innovation across disciplines and extending impact beyond campus to inspire environmental stewardship in the broader community. By implementing these actions HEIs can make significant strides toward campus sustainability, while significantly strengthening local and global mitigation efforts of climate change, pollution and biodiversity loss.

KEYWORDS

green campus, higher education institutions, sustainability, green policies, sustainable campus initiatives, climate change

1 Introduction

1.1 The global environmental crisis and the role of HEIs

The global environmental crisis poses an immediate and significant threat to the planet and its inhabitants (McCarthy, 2001). Characterized by escalating trends in climate change, biodiversity loss, and pollution, the crisis has a cascading effect impacting not only the environment but also the health of economies and societies worldwide.

These interconnected challenges demand a global, collaborative response with profound mitigation and adaptation strategies, requiring changes to current development patterns, production methods, and human consumption habits (IPCC, 2023).

Higher Education Institutions (HEIs) play a dual role in fostering sustainability. Firstly, they are responsible for educating future generations, equipping them with the knowledge and skills necessary to navigate the complexities of environmental challenges (Amaral et al., 2020). Secondly, HEIs can serve as exemplars of environmental stewardship by implementing sustainable practices across their operations and campuses (Beringer and Adomßent, 2008). This includes cultivating environmental awareness among students, developing and deploying innovative sustainable technologies, and demonstrating practical applications of sustainable principles in areas such as energy conservation, water management, waste reduction, and green building design (Kilkiş, 2017). By leading by example, HEIs can inspire broader societal change and contribute to a more resilient and sustainable future (Žalėnienė and Pereira, 2021).

1.2 Scope and objectives

This review aims to critically analyze existing literature on green campus initiatives, focusing on the environmental pillar of sustainability. It seeks to identify key strategies, challenges, and research gaps within this rapidly evolving field. Specifically, this review will examine:

- **Energy and Greenhouse Gas (GHG) Emissions:** Strategies for reducing energy consumption and GHG emissions, including energy-efficient building design and renewable energy integration.
- **Water and Runoff Management:** Sustainable water management practices, such as water conservation, rainwater harvesting, and runoff management.
- **Waste Management:** Initiatives for reducing waste generation and increasing recycling rates.
- **Green Buildings:** Design, construction, and operation of environmentally sustainable buildings.
- **Green Laboratories:** Strategies for reducing the environmental footprint of scientific laboratories.
  Eco-gardening: environmentally sustainable gardening methods for minimizing harm to the ecosystem and promoting biodiversity.

This review undertakes a rigorous and systematic analysis of existing literature to not only delineate the principal strategies for advancing green practices on HEI campuses, with a focus on physical and environmental sustainability, but also to critically dissect the obstacles hindering their implementation. Crucially, it will provide actionable recommendations to overcome these challenges and significantly enhance sustainability efforts within HEIs, culminating in a comprehensive assessment that will pinpoint critical areas requiring immediate research and strategic action to guide HEIs toward a truly sustainable future.

2 Methodology

This review presents an overview of over 180 scientific studies, reports and initiatives around the world which demonstrate strategies HEIs utilize to promote sustainability solutions in environment-related areas, specifically energy, water management, waste management, recycling, green buildings, laboratories, and gardening. The bibliographic data for this study were collected from the Web of Science database between August 2023 to December 2024. The initial search query used the following keywords: "sustainable campus," "green campus," "green laboratory," "economic and university," "waste and water and university," yielding 243 publications. In addition, we conducted a search for scientific papers related to the topics of the review including energy, greenhouse gas mitigation, water and waste management, green buildings and laboratories, and gardening.

To refine the results, we manually reviewed titles and abstracts, excluding articles that were not directly related to green campuses or sustainability in higher education. Exclusion criteria included non-peer-reviewed sources, articles in languages other than English, and studies not focused on sustainability topics. Articles selected for inclusion met the following criteria: (a) Peer-reviewed scholarly articles, (b) Articles written in English, (c) Published within the past 20 years unless deemed highly influential. We further expanded our dataset by reviewing articles that cited the initial publications and those cited by these publications, ensuring a comprehensive review of related literature.

Additionally, we conducted a targeted web search for green or sustainable campus initiatives, focusing on institutions recognized by the Sustainability Tracking, Assessment & Rating System (STARS), which is a transparent, self-reporting framework for colleges and universities to measure their sustainability performance (Dawodu et al., 2022). This supplementary search allowed us to include practical implementations alongside academic research. The selected publications were grouped by themes (e.g., energy efficiency, waste management) and analyzed using a qualitative coding framework to synthesize findings across studies.

3 Measures of HEI sustainability

In recent years, HEIs have increased their focus on sustainability, leading to the adoption of various methods and scales for advancing and evaluating campus sustainability (See for example Machado and Davim, 2023). Three primary approaches have emerged for assessing campus sustainability, namely, accounts, narrative, and indicator-based assessments

Abbreviations: BIQ-AUA, Benchmarking Indicators Questions-Alternative University Appraisal; BREEAM, Building Research Establishment Environmental Assessment Method; EAUC, Environmental Association for Universities and Colleges; EPA, Environmental Protection Agency; e-waste, electronic waste; GHG, greenhouse gases; HVAC, heating, ventilation, and air conditioning; HEIs, higher education institutions; LEED, Leadership in Energy and Environmental Design; PV, photovoltaic; ROI, returns on investment; RWH, rainwater harvesting; SESI, Stanford Energy Systems Innovation Program; WCED, World Commission on Environment and Development.

(Alghamdi et al., 2017; Dawodu et al., 2022; see Table 1). Accounts assessments involve the conversion of raw data into standardized units. Unfortunately, these assessments often cover only a limited number of sustainability aspects and lack clarity regarding the key components required for a sustainable institution. Additionally, although narrative assessments integrate various forms of data they may lack systematic organization, transparency, and consistency, making them less suitable for informed decision making and strategic planning. Indicator-based assessments are structured around specific indicators (e.g., Kwatra et al., 2016) and are widely regarded as one of the most comprehensive and representative approaches, offering easily measurable and comparable results that can effectively convey essential information to diverse audiences, including policymakers and the public (Alghamdi et al., 2017; Dawodu et al., 2022).

Although sustainability incorporates environmental, economic and social pillars, most measures emphasize the ecological pillar over the other two (Dawodu et al., 2022). Indeed, a review of the available measures for HEI sustainability revealed variations in the emphasis given to each of the three pillars (Alghamdi et al., 2017), with social aspects sometimes being left out entirely (e.g., Razzaq et al., 2023). Nonetheless, despite these differences, there are also commonalities. A recent review of campus assessment tools identified 12 dimensions that are usually present in all the tools (Dawodu et al., 2022):

- *Governance* includes vision, policy, gender equality, and staff management.
- *Operations-environmental* covers space use, audits, assets, land, and green tech.
- *Water* focuses on consumption, conservation, and recycling.
- *Waste* deals with hazardous waste, management, and renovation.
- *Building* addresses property and built infrastructures.
- *Transportation* concerns vehicles, public transportation, and parking.
- *Operational-social* relates to living conditions and human rights.
- *Operations-financial* pertains to sustainability investments.
- *Education* covers student and staff training.
- *Research* encompasses sustainable research and knowledge dissemination.
- *Engagement-campus* deals with public participation.
- *Survey* relates to sustainability-related surveys conducted among staff and students.

Of these dimensions, the most often used are operations-environmental (30%) and education (17%) (Dawodu et al., 2022).

4 Energy and greenhouse gas emissions

4.1 Reducing energy consumption

A significant aspect of the sustainable green campus is prioritizing energy management and conservation (Anthony, 2020; Sugiarto et al., 2022). Strategies for reducing energy demand in campus buildings involve various aspects of building design, including thermal insulation, wall thickness, window details, incorporation of sunrooms for passive solar heating, shading devices, and orientation of the main façades (Omrany and Marsono, 2016; Saboor et al., 2021). In addition, the integration of smart building technologies, such as smart lighting and heating, ventilation, and air conditioning (HVAC) systems, enhance efficient resource management (Anthony, 2020; Rebelatto et al., 2019).

Numerous HEIs worldwide have implemented diverse energy-saving strategies. For example, a Portuguese university redesigned the building envelope and heating system of one of its buildings, installing double-glazed windows, and adding thermal insulation to the roof, walls, and water pipes. They also developed an integrated management model for the heating system based on occupancy schedules (Soares et al., 2015). Other HEIs have focused on promoting on-campus conservation practices, installing energy-conserving technologies like electric sub-meters, and implementing awareness campaigns to encourage energy conservation among students, faculty, and staff (Oakland University, 2002). Studies have demonstrated the effectiveness of such campaigns in reducing electricity consumption in both classrooms and residence halls, for example: a study conducted at the University of Otago in Dunedin, New Zealand, demonstrated a 16.2% reduction in daily energy use in dormitories following the combination of visual prompts, daily feedback, and rewards (such as gift cards), compared to a 3.8% reduction in the control dorm, which received no interventions (Bekker et al., 2010). Another example is the energy reduction campaigns launched in 2021 and 2022 at Cornell University, which led to significant decreases in campus energy consumption, resulting in savings of 2,133,300 kWh, valued ∼$160,000.

In the design of an energy-efficient building it is necessary to take into consideration factors such as the orientation of the building on the land surface, natural light and natural ventilation. Such architectural elements (particularly exposure to solar radiation) not only affect the building's heating, ventilation and lighting (Bungau et al., 2022), but also maximize exposure to natural daylight, which can improve student performance. According to a report of the World Green Building Council, student performance improved in rooms lit by natural daylight, with test scores being 5–14% higher and learning speed, 20–26% faster (World Green Building Council, 2013). One of the most important factors in green building design is an advanced green roofing system that can reduce energy requirements for temperature control while providing natural insulation and mitigating water damage in the event of excess rainfall (Bungau et al., 2022). Green high-performance insulation materials, such as cellulose insulation or rigid foam boards, or a reflective roof coating can minimize heat transfer and promote optimal temperature control within a structure, thereby reducing the need for excessive heating or cooling (Bungau et al., 2022).

In a case study of an energy efficiency plan implemented in a building at a Portuguese university, the building's energy efficiency was improved by redesigning the building envelope and the heating system, as well as developing an integrated management model that controlled the heating system based on occupancy (Soares et al., 2015).

TABLE 1 Approaches to assessment of HEI sustainability.

Assessment approach	Description	Strengths	Limitations
Accounts	Converts raw data into standardized units	Simplifies comparison with aggregated data	Limited coverage of sustainability aspects; lacks clarity on key components
Narrative	Integrates various forms of data (texts, graphics, and tables)	Flexible and detailed; explores systemic interrelationships	Lacks systematic organization, transparency, and consistency
Indicator-Based	Structured around specific indicators (e.g., measurable and comparable results)	Comprehensive, representative, and suitable for diverse audiences	Requires robust indicator selection and may focus on quantifiable aspects

In addition to the energy-efficient design of campus infrastructure, reduction in energy consumption can also be achieved by promoting on-campus conservation practices (Faghihi et al., 2015). Such conservation efforts should encompass both the installation of energy-conserving technologies, such as electric sub-meters, and the implementation of awareness campaigns to promote energy conservation on the part of students, faculty, and staff (Anthony, 2020). Studies have shown that campaigns for reducing electricity consumption directed at students and faculty can be effective in both classrooms and residence halls (Maistry and Annegarn, 2016; Sintov et al., 2016).

4.2 Renewable energy production

Another aspect of enhancing energy efficiency on campuses is the production of renewable energy. To achieve this goal and to strive for energy independence, several universities have chosen to install photovoltaic systems on the rooftops of campus buildings (Hasapis et al., 2017; Radosevic et al., 2022). The clean energy produced by these systems can generate electricity for electric cars on campus, contribute to the national grid (Chowdhury et al., 2018), and reduce the university's reliance on electricity providers that utilize fossil fuels (Rebelatto et al., 2019). Likewise, the production of electricity from solar energy has now been integrated into the efforts of some HEIs to reduce their CO_2 emissions (Chowdhury et al., 2018; Fonseca et al., 2018; Timmons and Weil, 2021) as one way of converting campus buildings into zero-energy buildings. In a case study of a renovation plan for a university building in Portugal (Fonseca et al., 2018), the designers reduced the energy load, improved energy efficiency, and made provisions for a renewable energy supply and energy storage. In this case, EU directives and regulations, in particular those concerning minimum efficiency performance standards and labeling for lighting and office equipment, had a significant impact on reducing electricity demand (Fonseca et al., 2018). It may therefore be concluded that mandatory national and international standards will facilitate the energy efficiency process in HEIs (Lee and Lee, 2021). Four other illustrative examples may be cited: (1) the collaborative solar-panel project of University of Brighton (UK) with the Brighton Energy Co-op, which is expected to produce 205,000 kWh annually and save the University over £185,000 and over 1,000 tons of carbon over a 20-year period. Upon the expiration of the lease, the university will acquire ownership of the panels at no additional cost and will benefit from the electricity generated without incurring further expenses. (Brighton Energy Cooperative, 2017); (2) Stanford University (USA) promotes the use of renewable energy, including thermal and solar power. Through the establishment of the Stanford Energy Systems Innovation (SESI) program, the university activated its solar generation stations, achieving a complete transition from fossil fuel-based energy to renewables. This shift contributed to an 80% reduction in campus emissions from peak levels (https://sesi.stanford.edu/energy-systems/central-energy-facility); (3) the comprehensive solar program of Arizona State University (USA), which has over 53 MW_{dc} equivalent solar generating capacity from both on-site and off-site components. The on-site component extends to four campus locations and the university Research Park, it consists of nearly 90 solar systems and in 2023 yielded 34,708,060 kWh (Arizona State University, 2024); and (4) The energy efficient actions of the University of Passo Fundo (Brazil), which include a transition to LED lamps, the proposed installation of solar power systems; and a transition to a free energy market model, enabling the selection of suppliers that guarantee electricity from renewable sources (Salvia et al., 2018).

The above examples demonstrate that harnessing solar energy by installing solar photovoltaic (PV) systems will facilitate a reduction in the use of electricity from the grid, offering HEIs a cost-effective and sustainable energy solution, with declining costs and favorable returns on investment (ROI). Rooftop PV installations demonstrate payback periods of 3.9 to 8.4 years, significantly reducing electricity expenses and carbon emissions (Paudel et al., 2021; Mandi, 2017). Grid-connected systems are particularly economical, offering lower energy costs compared to standalone systems (Dursun and Altay, 2018).

It is important to note that daytime electricity usage on HEI campuses is enormous and that the amount of energy consumed on campuses is continually rising due to the increase in student numbers and the expansion of facilities. Yet, universities and colleges usually have extensive flat roof spaces, which simplifies the installation of solar panels. Harnessing solar energy could offset their utility costs, while reducing the GHG emissions that would be produced from purchased electricity or natural gas.

While upfront capital investment for PV systems is substantial, institutions can mitigate costs through government incentives, external funding, and phased implementation. Green fiscal policies and financial development strategies further ease budget constraints. Additionally, feed-in tariffs or net metering enable HEIs to generate revenue by selling excess electricity back to the grid. Over time, solar PV systems reduce operating costs, enhance energy independence, and serve as research platforms that attract funding. These systems also help institutions meet sustainability goals while boosting their reputation as environmentally responsible leaders. Despite initial financial hurdles, solar PV systems provide HEIs with long-term economic and environmental benefits (Lottu et al., 2023). By leveraging funding opportunities and strategic planning, institutions can transition to renewable energy while achieving cost savings and sustainability objectives.

The installation of PV systems, a sustainable and cost-effective choice, would further enhance campus buildings' sustainability performance, as shown by the above example of the recent installation of solar panels at the University of Brighton, which resulted in ∼33% savings on the cost of grid electricity. Additionally, the new clean-energy system provides security against fluctuating energy costs and contributes to reducing the University's carbon footprint.

4.3 Reduction of GHG emissions in HEIs

Reducing GHG emissions is a crucial step toward achieving sustainable and environmentally responsible campuses. Two primary approaches for GHG reduction in HEIs are decarbonization and carbon pricing. Decarbonization involves transitioning away from fossil fuels and toward renewable energy sources and energy-efficient practices. Carbon pricing, on the other hand, aims to incentivize emissions reduction by assigning a financial cost to GHG emissions, encouraging individuals and institutions to adopt more sustainable practices.

Decarbonization aligns with the missions of many HEIs, namely, teaching about climate change, researching climate-change mitigation, and leading by example by reducing their own GHG emissions (Timmons and Weil, 2021; Kiehle et al., 2023). However, decarbonization in HEIs vs. other institutional settings is more challenging, as HEIs are like "small cities," with numerous activities that use fossil fuels directly and indirectly, as well as other activities that generate GHG (Timmons and Weil, 2021). Although purchasing carbon offsets is a sanctioned method for claiming reductions in GHG emissions, Timmons and Weil (2021) argue that HEIs should take a leading role in dramatically reducing GHG emissions rather than relying primarily on offsetting.

Another strategy for decarbonization concerns reducing emissions through carbon pricing. As small cities, HEIs have the autonomy to make independent decisions regarding buildings, operations and maintenance. North American universities, such as the University of British Columbia, Yale and Arizona State, charge fees for university-related air travel and other environmentally harmful activities. These funds are then used to purchase local and community-based offsetting initiatives, such as tree planting projects, that match the emissions generated. University College London initiated a similar program, but instead of taxing environmentally harmful activities, rebates were offered as incentives to encourage individuals to decrease their carbon emissions (Lee and Lee, 2021).

Lee and Lee (2021) demonstrated how the implementation of carbon pricing mechanisms could reduce emissions from waste management in HEIs. Utilizing hypothetical carbon revenues generated by 37 HEIs in the USA, they postulated that if all 37 institutions were to implement internal carbon pricing at the cost of \$75/ton CO_2 eq for the total amount of emissions generated from their campus waste, they would generate revenues of more than 26 million USD. These revenues could, for example, be used to install 1,700 solar panels or to plant ∼260,000 mid-sized trees on and around their campus, further contributing to a reduction in CO_2 emissions.

Since June 2020, over 1,200 universities and colleges have joined the UN's "Race to Zero" campaign, led by the Environmental Association for Universities and Colleges (EAUC) and Second Nature with the support of the UNEP (United Nations Climate Change, 2020; EAUC, 2024). Of these universities, 548 have committed to reducing their carbon emissions to zero by 2050, at the latest. We note that the HEIs that have pledged to "Race to Zero" represent ∼10 million students, which is <5% of the world's 220 million students (United Nations Climate Change, 2020).

4.4 Challenges in reducing energy consumption and GHG emissions

HEIs are like "small cities"—HEIs may be comparable to small municipalities in that they are spread over large areas, housing an assorted populace, with multifaceted activities and operations taking place on their campuses (Mustafa et al., 2022). Achieving energy efficiency and decarbonization in HEIs can indeed pose challenges, given that many of these activities still rely directly and indirectly on fossil fuels, thereby contributing to the generation of GHG (Timmons and Weil, 2021).

Administration commitment—The commitment of university administrations to promote sustainability and energy efficiency is pivotal to the advance to green and sustainable campuses. Contrarily, a lack of commitment on the part of university administrations is one of the major challenges to achieving energy efficiency improvements and advancing renewable energy projects on campus. Such a commitment is especially important for budget allocations and for promoting educational programs (Leal Filho et al., 2019).

Commitment of staff and students—Several studies utilizing community surveys conducted on university campuses have highlighted the critical role of behavioral change in energy efficiency and decarbonization initiatives among members of the campus community (Mustafa et al., 2022; Rebelatto et al., 2019; Soares et al., 2015; Udas et al., 2018). Cultivating a long-term behavioral change toward energy efficiency and reducing individual carbon footprints could assist in the implementation of energy efficiency projects across campuses (Leal Filho et al., 2019).

Calculating universities' carbon footprint and the impact of mitigation activities—There are currently no internationally adopted guidelines for calculating carbon footprints in HEIs (Mustafa et al., 2022). Case studies from HEIs around the world reveal that institutions utilize diverse methods to perform these calculations. Carbon footprint assessments often include energy-related emissions, including those from electricity and heating on campus, as well as carbon emissions resulting from work-related travel by university faculty and staff. Additional calculations include emissions from activities that require fuels, such as diesel, natural gas, organic fertilizers, as well as emissions stemming from the consumption of purchased electricity (Udas et al., 2018).

To achieve their energy efficiency and decarbonization goals, HEIs must operate on two levels. First, HEIs must make the necessary improvements and adjustments to their buildings, equipment, and purchased electricity sources. Second, HEIs must educate the campus community regarding smarter energy consumption practices. As this review shows, these two levels are interlinked, and a successful transition to a clean, energy-efficient campus must address both levels. Commitment of the institution's administration and the availability of mandatory standards and guidelines at the state level will make a pivotal contribution to the successful design and implementation of energy efficiency and decarbonization strategies in HEIs.

5 Water and runoff management

To effectively manage water resources and minimize their environmental impact, HEIs must adopt a comprehensive approach that encompasses three key strategies: water conservation, rainwater harvesting (RWH), and runoff management. Water conservation techniques aim to reduce water consumption through the implementation of efficient technologies and practices. RWH systems capture and utilize rainwater, providing an alternative water source and reducing reliance on municipal supplies. Runoff management strategies, on the other hand, focus on mitigating the negative impacts of stormwater runoff by employing green infrastructure solutions to reduce runoff volume and improve water quality. These strategies not only aim to conserve water resources and enhance water quality but also ensure the long-term availability of water for diverse campus needs (Tan et al., 2024; Powell and Larsen, 2013) (see Figure 1).

5.1 Water conservation

Water conservation techniques are essential for minimizing water waste and optimizing water use on campuses worldwide. According to the WaterSense program of the US Environmental Protection Agency (EPA), educational facilities account for ∼6% of total water use in commercial and institutional facilities in the USA. The largest water demands on educational campuses typically stem from restrooms, landscaping, heating and cooling, and cafeteria kitchens (US EPA, 2017). Estimates of the WaterSense program suggest that implementing water-efficient strategies on HEI campuses can reduce energy and water use by 10 and 15%, respectively, along with decreasing operating costs by 11% (US EPA, 2017).

A variety of water conservation techniques have been employed in HEIs. These include the installation of low-flow plumbing fixtures, such as faucets, toilets, and showerheads, and/or dual-flush toilets, all of which can lead to significant water and energy savings. Research indicates that the use of low-flow showerheads can decrease the flow rate by 15%, corresponding to a 1.5% improvement in energy efficiency (Zhou et al., 2019). Similarly, the installation of low-flow fixtures in residential housing has been found to reduce per capita indoor water use by 6.4% and 1.5–2.1% for low-flow showerheads and toilet displacement devices, respectively (Whitcomb, 1990). Furthermore, the implementation of efficient plumbing systems has been demonstrated to reduce residential water consumption by 3.5% (Agarwal et al., 2022). Low-flow plumbing fixtures have been extensively installed in dormitories, academic buildings, and recreational facilities across campuses (Cupido et al., 2016; Kiraz, 2018). In Ghana, a study conducted at Kumasi University identified bathroom use as the primary source of water consumption. The study proposed the installation of water-efficient showerheads, predicting a reduction in annual water demand of over 30% with a viable economic payback within six and a half years (Oduro-Kwarteng et al., 2009).

Leak detection and repair programs are also vital, as leaks can account for a substantial portion of water loss in older infrastructures. Both applied and theoretical studies have addressed this issue. Two groups working in Europe both highlighted the importance of early detection of leaks in water supply networks, with one modeling leakage detection and the other focusing on the use of acoustic emission measurements (Holnicki-Szulc et al., 2005; Martini et al., 2016). In practice, some universities have already adopted leak detection technologies, incorporating advanced methods, such as sensors and smart meters to monitor water usage and identify leaks in real time, allowing for prompt repairs and significantly reducing water waste (Sánchez and Esquerre, 2018; Zellner, 2014).

Irrigation constitutes one of the largest water demands on higher education campuses. As such, water-efficient landscaping, prioritizing drought-resistant plants, and efficient irrigation systems are all crucial for decreasing water demand for campus irrigation. According to a survey conducted in 2013 by the Texas Regional Alliance for Campuses Sustainability (TRACS), the most widely used water conservation techniques for irrigation among the HEIs participating in the Alliance were the use of native or adapted plants and drip irrigation (Zellner, 2014) (see also, Section 9). Smart irrigation controllers (that adjust watering schedules based on weather conditions and soil moisture levels, thus preventing over-watering and ensuring efficient use of water for landscaping) have been installed at the University of California, Irvine (UCI), whose centralized irrigation control system adjusts watering schedules based on ambient conditions, resulting in a significant reduction in water usage.

Educating the campus community about water-saving practices is also important for fostering a culture of sustainability within HEIs. Initiatives such as workshops, sustainability fairs, and digital campaigns have been shown to raise awareness among students, faculty, and staff about the importance of conserving water (Keramitsoglou and Tsagarakis, 2011; Marinho et al., 2014). By incorporating interactive learning experiences and practical demonstrations, such as the proper use of low-flow fixtures and the benefits of RWH, educational programs can empower individuals to adopt water-efficient behaviors.

Water conservation efforts on university campuses in Brazil and Mexico illustrate varied rates of success and demonstrate the accompanying challenges facing such efforts in regions experiencing water scarcity (Marinho et al., 2014; Oduro-Kwarteng et al., 2009; Velazquez et al., 2013). The AGUAPURA program

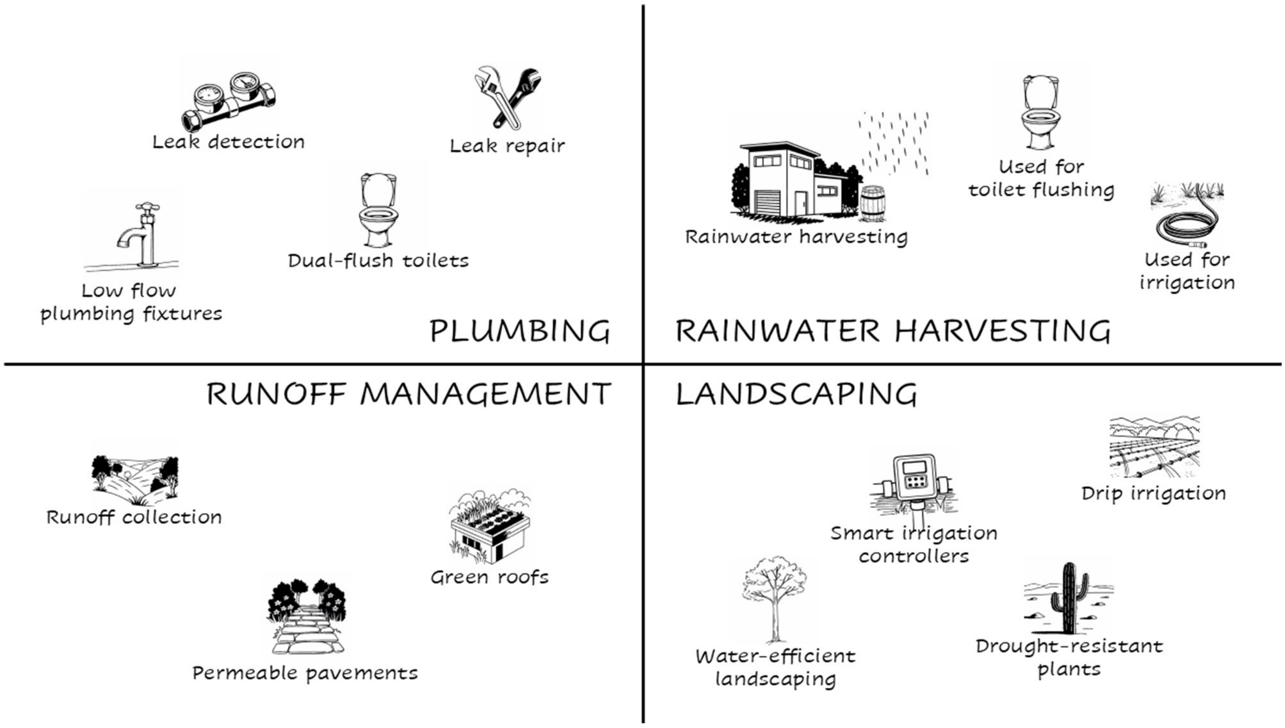

FIGURE 1
Strategies for water conservation.

at the Federal University of Bahia, which operated from 1999 to 2008, halved the water usage per capita by monitoring consumption practices and leveraging online reporting to raise public awareness regarding water consumption (Marinho et al., 2014). The University of Sonora, Mexico, introduced an ISO 14001-certified sustainability management system to reduce water use, emphasizing decisions based on an efficiency-benefit analysis rather than purely cost-benefit considerations (Velazquez et al., 2013). The above case studies underscore the importance of tailored, context-specific strategies for effective water conservation in higher education settings.

5.2 RWH systems and water recycling

RWH systems are designed to capture, store and utilize rainwater, contributing to sustainable water management. Their implementation in HEIs offers multiple benefits. First, they promote sustainability on campuses globally, while reducing reliance on municipal water supplies (Adugna et al., 2018; Harb, 2015; Zang et al., 2021). Second, they provide an alternative water source for non-potable uses, such as irrigation, toilet flushing, and cooling systems, consequently reducing the overall water footprint of the campus (Ravelo-García et al., 2023). Third, they play a crucial role in stormwater management by mitigating the impact of runoff on local waterways and reducing the risk of flooding and erosion (Huang et al., 2021). This aspect of RWH is particularly important in urban areas, where impermeable surfaces can lead to increased runoff and pollution.

As with other sustainable practices, RWH systems in HEIs also have an educational value, serving as living laboratories and offering hands-on learning opportunities. Students across various disciplines (e.g., environmental science, engineering) can explore the design, implementation, and maintenance of RWH systems, gaining valuable insights into water conservation and management practices (Ghis, 2017). Moreover, the integration of RWH systems into campus infrastructures reflects HEIs' commitment to sustainability and environmental stewardship. It sends a strong message to students, staff, and the broader community about the importance of water conservation and the practical steps that can be taken to achieve it.

5.3 Runoff management

Effective runoff management practices, such as the construction of green roofs, permeable pavements, and rain gardens, are essential for minimizing the environmental impact of stormwater (Sharma and Malaviya, 2021; Zahakis et al., 2015; Pistocchi, 2020). These practices not only reduce the volume of runoff but also improve water quality by filtering out pollutants before they reach water bodies (Liu et al., 2017). The implementation of these green infrastructure elements in campus planning and design contributes to the creation of resilient and sustainable urban landscapes. Several HEIs in different parts of the world have applied water and runoff management practices, implementing innovative solutions to address the challenges of water scarcity and pollution. For example, the University of Delaware implemented a rain garden initiative that conserves water, promotes groundwater recharge, and reduces waterbody pollution by capturing and infiltrating stormwater. This green infrastructure also enhances biodiversity by using native plants, which are already adapted to natural fluctuations in water availability (Grehl and Kauffman, 2007). The University of Pennsylvania's Stormwater Master Plan, which includes green roofs, permeable pavements, and rain gardens to manage stormwater, reduce runoff, and improve water quality, demonstrates a commitment to sustainable campus development and environmental stewardship (University of Pennsylvania, 2013). Universitas Sebelas Maret in Indonesia has constructed 117 infiltration wells and over 500 biopower infiltration units to enhance shallow groundwater reserves, facilitating RWH and enhancing soil moisture levels. Additionally, rainwater that is not accommodated by the infiltration wells is directed to Danau UNS, a lake designed to maintain groundwater balance (Widodo et al., 2021). Initiatives such as these collectively strive to manage rainwater effectively, thereby mitigating surface runoff and supporting groundwater replenishment.

5.4 Challenges in water management

Despite the progress made in water and runoff management, HEIs face various challenges hindering the wider adoption and full realization of potential benefits. One significant hurdle is the lack of sufficient financial resources, which often restricts the implementation of comprehensive water management systems. The absence of robust institutional frameworks, including administrative support and interdepartmental coordination, can further impede advancements in this area. Moreover, maintaining sustained community engagement remains crucial for the success of any water management initiative. Without continuous efforts to educate and engage students, faculty, and staff, conservation efforts may not be fully effective. To address these challenges, a collaborative, multi-faceted approach is essential. This includes securing adequate funding to support the implementation and upkeep of necessary infrastructure, fostering a campus-wide culture of sustainability through strong leadership and shared commitment to conservation goals, and integrating water and runoff management principles into curricula and research activities to raise awareness and create valuable learning opportunities. To ensure the widespread adoption and long-term effectiveness of these systems, further research is needed to evaluate their economic feasibility and maintenance requirements. By actively tackling these obstacles, HEIs can create more sustainable and resilient water management systems that benefit both the campus community and the environment.

6 Waste management

Waste management encompasses the processes and actions required to handle waste from its inception to disposal, including policy formulation, waste collection, transportation, handling, and disposal (Pongrácz and Pohjola, 2004; Iqbal et al., 2024). It also involves monitoring, regulation, technological advancements, and economic mechanisms aimed at sustainability. Reducing, reusing, and recycling waste offer sustainable alternatives to incineration and landfilling (West and Allen, 2015).

Higher Education Institutions (HEIs) produce diverse waste streams, such as wet, dry, organic, non-organic, and contaminated waste. Many HEIs have implemented waste management initiatives, often influenced by national sustainable development policies or local authority regulations (Ebrahimi and North, 2017; Nolasco et al., 2020; Rohlig, 2022; Velazquez et al., 2006). These initiatives, known as zero-waste programs, aim to maximize recycling and reduce waste sent to landfills, incinerators, and oceans (Moreira and Rutkoskwi, 2021).

HEIs around the world have implemented waste management initiatives on their campuses (Ebrahimi and North, 2017; Nolasco et al., 2020), where the intra-campus waste management policy often depends on the sustainable development policies of specific countries or the regulations of the local authority where the university is located (Ebrahimi and North, 2017; Rohlig, 2022; Velazquez et al., 2006). HEI policies and strategies, also referred to as zero-waste programs, aim to enhance and maximize the amount of waste recycled on campus (Moreira and Rutkoskwi, 2021). They also aim to reduce the amount of waste generated by the HEI and to divert as much waste as possible from landfills, incinerators, and oceans (Moreira and Rutkoskwi, 2021; University of Oregon, n.d.).

6.1 Waste management policies

Sustainable waste management practices of HEIs that include the implementation a circular economy model will reduce the linear consumption model (extraction, production, consumption, and disposal) and promote circularity (Aithal and Aithal, 2023) by minimizing waste production and maximizing resource utilization. By adopting policy instruments, such as purchasing policies (e.g., favoring eco-friendly products) and recycling initiatives, HEIs can encourage sustainable waste management practices on campus (Ebrahimi and North, 2017). Initiatives could include the provision of recycling stations across campus for mobile phones, pens, markers, and highlighters, and the implementation of e-waste management policies to properly recycle electronic waste and donate old, but functional, electronic devices to charity. Other policies can also be implemented to encourage waste minimization, such as the careful planning of projects to minimize offcuts. Moreover, some campuses, such as Case Western Reserve University, have established "give and take" stores that accept second-hand donations from students and allow other students to shop for free (National Wildlife Federation, 2011). Some universities have specific targets for waste reduction and recycling. For example, McGill University's Waste Reduction and Diversion Strategy 2018–2025 aims to improve waste system logistics and set institutional priorities (McGill University, 2017).

6.2. Solid waste management

6.2.1. Food and organic waste

Organic waste comprises any biodegradable material that derives from a plant or animal and is generated from food scraps or wet waste, but it may also comprise dry organic waste, such as yard trimmings, paper, and wood. The primary methods for treating wet organic waste on campuses involve composting (Ali, 2003; Kadir et al., 2016). Composting organic food reduces the amount of waste sent to landfills and incinerators, and also helps conserve water, improve soil quality, and mitigate climate change (Ali, 2003; Hanninen et al., 2012).

Donating food as a method to prevent food waste also addresses the problem of food insecurity within a community (Warshawsky, 2024). Food donation programs collect surplus or unsold food from campus dining halls or catering services, or after events, and distribute it to local food banks and shelters. Food donation programs not only reduce waste, but also save money, enhance social responsibility, and foster partnerships with the community.

6.2.2. Solid dry waste

Solid waste on campuses is defined as any non-liquid material that is discarded by the staff and students on the campus, such as paper, plastic, metal, food containers, and yard waste (Gherheş et al., 2024). Sending waste to recycling centers is optional in some countries and mandatory in others. The Hebrew University of Jerusalem, for example, opts to recycle a large portion of such recyclable waste comprising batteries, toners, paper, cardboard, plastic bottles, electronic equipment, and glass (Hebrew University, 2024). The practice of recycling solid waste on campuses is essential for environmental sustainability, resource conservation, educational purposes, and cost savings.

6.2.3. Solid organic waste

Paper recycling is the process of turning wastepaper into new paper products, such as notebooks, envelopes, or cardboard boxes (Geller et al., 1975; Mama et al., 2022; University of Oregon, n.d.). Paper recycling can save trees, water, energy, and landfill space, and reduce GHG emissions and pollution (Ebrahimi and North, 2017; Mama et al., 2022; Nolasco et al., 2020). Some campuses have implemented paper recycling programs, such as the University of California, Berkeley (see Table 2).

Wood can be repurposed in various construction or building projects, including those on HEI campuses. For example, old furniture can be refurbished, or construction waste can be reused in new building projects (Green Office, 2024; Parvez et al., 2019). Wood can also be recycled into a variety of products, including mulch, compost, and particleboard (Green Office, 2024). In parallel, it is possible to implement waste minimization strategies aimed at reducing the amount of wood waste in campus building projects (Green Office, 2024; Shankar et al., 2017).

6.2.4 Non-organic waste

Plastic recycling is the process of converting waste plastic into new plastic products, such as bottles, bags, or containers. Plastic recycling can conserve petroleum, reduce waste, and mitigate plastic pollution in the oceans (Godship, 2007; Zhang et al., 2020; Preka et al., 2022). An exceptional example is that of the University of California, Berkeley, which is establishing its first holistic Plastic Recycling and Recovery Facility. The project involves transporting the university's plastic and recycling waste to a dedicated facility located at the UC Berkeley Global Campus. This project will allow the University of California to recycle 17 tons of municipal solid waste from the campus each day (University of California, Berkeley, 2021).

Electronic waste (e-waste) and **metal** recycling starts with the disassembly of discarded electronic devices and separation of components from old computers, mobile phones, and other electronics (Abulia and Lestari, 2024; Namias, 2013). The components can then be processed to extract metals—both high value metals that can be reused and toxic waste. Importantly, metal recycling can conserve energy, reduce mining, and reduce GHG emissions and pollution levels (Gerold et al., 2024). Metal recycling programs have indeed implemented on some campuses, such as the University of Texas at Austin (see Table 2).

Glass recycling is the process of turning waste glass into new glass products, such as bottles, jars, or windows. Glass recycling can conserve energy, reduce raw material use, and reduce GHG and pollution levels (Ogundairo et al., 2019). Some campuses have implemented glass recycling programs, such as the University of Wisconsin-Madison (see Table 2).

6.3 Minimizing waste

Switching to reusable items, such as beverage containers, utensils, plates, and bags, is another effective way to reduce waste and conserve resources (Coelho et al., 2020; Zhao et al., 2021). Reusable items reduce the usage of single-use disposable items, which usually end up in landfills or in marine or land environments. Additionally, reusables save money, energy, and water in the long run (Zhao et al., 2021). Some campuses have adopted policies or incentives to encourage the use of reusable items, such as Lehigh University, which reduced the use of disposable clamshell take-out containers by introducing a reusable eco container program (Lehigh University, n.d.).

6.4 Challenges in waste management

While HEIs strive to implement robust waste management policies, several challenges impede their efforts to minimize waste and adopt sustainable practices. National waste management regulations and capabilities play a crucial role, as HEIs must comply with existing regulations and rely on available infrastructure for waste processing and disposal. Variability in local and national regulations can create inconsistencies in waste management practices across different campuses, requiring flexible and adaptable policies. The effectiveness of HEIs' waste management programs is also heavily influenced by the availability of adequate

TABLE 2 Summary of waste management practices on campuses.

Waste type	Methods	Examples/case studies	Outcome
Food and organic	Composting, Food Donation	Kent State University (Warshawsky, 2024)	Over 100,000 pounds of food diverted from landfill since 2011 and supplying over 80,000 meals to the community
Solid dry	Recycling	Hebrew University of Jerusalem (Hebrew University, 2024)	Recyclable waste including batteries, toners, paper, cardboard, plastic bottles, electronic equipment, and glass
Solid organic	Paper Recycling, Wood Repurposing	UC Berkeley (University of California, Berkeley, n.d.); Green Office (Green Office, 2024)	Over 1,800 tons of paper recycled in 2019, saving over 30,000 trees and 7 million gallons of water
Non-organic	Plastic, E-Waste, Metal, Glass Recycling	UC Berkeley (University of California, Berkeley, 2021); University of Texas at Austin (Thurston, 2017); University of Wisconsin-Madison (Wisconsin Department of Natural Resources, 2022)	Over 200 tons of glass recycled in 2019, saving over 300 barrels of oil and reducing CO_2 emissions by over 300 tons. Recycled metal - saving over 4,000 MWh of electricity and reducing CO_2 emissions by over 2,000 tons of

infrastructure and resources at the national level, such as recycling facilities and composting plants.

Furthermore, engaging stakeholders and promoting behavioral change within the campus community is paramount. Without active participation from students, faculty, and staff, waste reduction and recycling efforts may face significant challenges. HEIs need to invest in educational initiatives to raise awareness about the importance of sustainable waste management and to provide practical guidance on how individuals can contribute to these goals. By collaborating with local authorities and national waste management providers, HEIs can leverage existing resources and expertise to develop more effective and sustainable waste management solutions.

Educating and engaging stakeholders, including students, faculty, staff, and visitors, is essential for raising awareness and promoting a behavioral change toward waste prevention (Debrah et al., 2021). Education and awareness campaigns can employ various means and methods, such as posters, flyers, newsletters, social media, workshops, webinars, contests, and events, to inform and inspire stakeholders regarding the available methods of waste prevention and their benefits (Posner and Stuart, 2013). Additionally, such campaigns can provide students and staff with practical tips and tools to reduce their waste footprint (Posner and Stuart, 2013).

Waste prevention and reduction policies are among the most effective for managing sustainable resources and waste, with recycling efforts typically targeting organic and solid waste generated on campuses. Investment in education, including campaigns, workshops, and events, is essential for raising awareness and promoting behavioral changes toward waste prevention.

7 Green buildings

Green buildings combine different aspects of all the previously discussed topics, including waste and runoff management, reduced utilization of water and energy, and reduced GHG emissions. In recent years, HEIs across the world have adopted green building policies and practices for their new campus buildings and major renovations. According to the US EPA, green building is “the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building’s life-cycle from siting to design, construction, operation, maintenance, renovation, and deconstruction” (EPA, 2016). Also known as sustainable or high-performance buildings, green buildings take into account the comfort, economy, durability, and utility elements of a building (US EPA, 2016).

Green building practices and policies on higher education campuses focus on minimizing the use of non-renewable resources, reducing energy consumption, managing waste efficiently, creating healthier learning environments and promoting environmental awareness and stewardship among students (Hopkins, 2016). HEIs track their progress, set goals for improvement, and demonstrate their commitment to sustainability by adhering to green building certification programs or systems that measure and rate the level of environmentalism and sustainability of buildings. Green building certifications and rating systems have been established by several countries, with the American-established Leadership in Energy and Environmental Design (LEED) being the most widely used and desirable green building certification in the world. LEED certifications focus on lower operating costs, healthier and more productive building spaces, energy and water conservation, waste diversion, and lower GHG emissions (U.S. Green Building Council, 2016). The University of California, Berkeley announced that all new buildings and major modifications will achieve a minimum of LEED Gold certification, this project is in progress (University of California, Berkeley, 2025). In 2024, The University of California, LA (UCLA) declared that all new construction must be certified LEED Gold or higher (University of California, LA, 2021). The University of Wyoming has committed to building LEED-Silver standards or better, for example, The UW Visual Arts Building received the platinum LEED certification, The building is projected to produce 54% less carbon dioxide relative to traditional buildings through evaporative cooling, exhaust heat recovery, natural ventilation, and other innovative approaches. The building also produces renewable energy from an on-site solar thermal array which supplies hot water for heating purposes (University of Wyoming, n.d.). In Israel, the relevant certification is the 5281 Green Building Standard Certification. The “EcoBuilding” on the Tel Aviv University Campus (housing the Department of Environmental Studies of the Porter School of the Environment and Earth Sciences) was the first campus building ever to attain a LEED Platinum certification. The data collected through rating systems such as LEED can be used to communicate achievements, engage stakeholders, and continuously refine sustainability strategies. These rating systems are usually based on an indicator-assessment strategy.

Universities and colleges promoting construction or renovation of buildings following green building standards must consider the proper siting of buildings during the design phase. Such considerations are crucial for reducing emissions and protecting the natural environment on the campus. The consideration of existing structures within campuses for reuse or renovation significantly contributes to energy efficiency, the conservation of natural resources, and the preservation of historical and cultural values. Prioritizing the preservation of existing green spaces and natural habitats on campus is crucial when selecting sites for the construction of new buildings on campus. In addition to proper siting, the careful selection of building materials can minimize construction waste, deconstruction waste and other environmental burdens associated with a building's lifecycle (Huang et al., 2020).

Green building materials, also known as sustainable or eco-friendly materials, are generally considered environmentally friendly or environmentally responsible throughout their whole life-cycle (Franzoni, 2011). Moreover, green building materials are sourced from recycled, renewable, reclaimed, or locally sourced materials and have a lower carbon footprint. The use of recycled building materials, along with efficient on-site reuse/recycling and treatment of construction and demolition wastes, can reduce the energy consumption associated with waste transportation. Furthermore, designing for deconstruction in a manner that allows resources to be economically recovered and reused will facilitate the recycling or reuse of materials when a building reaches the end of its life (Huang et al., 2020; Kamali et al., 2019). Green building materials are also non-toxic/non-hazardous, with low levels of emissions, thereby contributing to resource conservation, minimal waste generation, and healthier indoor environments (Franzoni, 2011; Huang et al., 2020) (see Figure 2).

7.1 Challenges in green buildings

The adoption by campuses around the world of green building practices and policies faces multiple barriers. These include a lack of environmental awareness, limited interest and motivation, insufficient information and knowledge, and inadequate communication among various stakeholders (Blanco-Portela et al., 2017; Dahle and Neumayer, 2001; Horhota et al., 2014; Wright and Wilton, 2012). The lack of understanding regarding the environmental and economic benefits of campus sustainability initiatives among faculty and staff, coupled with the time constraints resulting from prior commitments to other groups and causes, produce an overall disengagement (Horhota et al., 2014). Additionally, the perceived lack of relevance of such initiatives or ignorance concerning the benefits of campus sustainability can also create resistance to change. Additional common barriers to adopting green building practices into HEIs include limited motivation on the part of potential environmental stewardship representatives due to the indifference of senior management, a lack of institutional interest, resistance to change, and deficiencies in institutional leadership (Cupido et al., 2010). Finally, the increased upfront costs to build green (vs. conventional) buildings, the perception that "green" is just an added feature and therefore an added cost, and the mixed results obtained for operating costs all hinder the process of adopting green building practices on campuses (Blanco-Portela et al., 2017; Hopkins, 2015; Horhota et al., 2014). This is particularly the case for HEIs with limited financial resources or insufficient funding mechanisms dedicated to green building initiatives. Some of these barriers can be addressed by examining student perceptions, encouraging knowledge acquisition in HEIs, strategic campus planning, providing financial incentives, appointing a campus sustainability officer, and promoting green building initiatives (Hopkins, 2016).

8 Green laboratories

Academic research has been instrumental in revealing the causes and impacts of climate change, environmental pollution and biodiversity loss, as well as in developing solutions to these issues. Research and teaching in universities, research institutes, hospitals, and private companies have historically depended on different types of laboratories, from wet and dry labs to computational facilities. While crucial for advancement, laboratory-based scientific progress has come with considerable environmental consequences (Greever et al., 2020). Research activities, especially in life sciences and medical laboratories have been documented to generate significant environmental impacts, resulting in a substantial ecological footprint (ALLEA, 2022; Greever et al., 2020). With their energy-intensive equipment, high infrastructure maintenance costs, chemical waste production, animal housing, big-data analysis and storage and high consumption of single-use items, laboratories are significant contributors to environmental pollution (Borgermann et al., 2022; Rae et al., 2022; Urbina et al., 2015). Indeed, laboratories typically consume 5 to 10 times more energy than equivalently sized commercial spaces, and even up to 100 times more in the case of clean rooms (US EPA, and US Dept of Energy Efficiency and Renewable Energy, 2008). In 2014, biomedical and agricultural research institutions, numbering around 20,500 worldwide, generated an estimated 5.5 million metric tons of lab plastic waste, representing nearly 2% of global annual plastic waste (Urbina et al., 2015). The carbon emission intensity of the global pharmaceutical industry alone in 2015 was evaluated to be 55% higher than that of the global automotive industry (Belkhir and Elmeligi, 2019). In 2019, the healthcare sector's climate footprint, mainly from hospitals and laboratories, constituted 4.4% of global emissions, equivalent to the output of 514 coal-fired power plants (Healthcare Without Harm ARUP, 2019). Although these statistics are concerning, they also present numerous possibilities for implementing measures to mitigate emissions and pollution on a broader scale, with the potential for positive environmental impact.

In the past few decades, researchers at universities and research institutions worldwide have recognized the need to reduce their ecological footprint and to implement greener practices in their laboratories (Aghamolaei and Fallahpour, 2023; Rae et al., 2022; Ragazzi et al., 2023). Although universities are theoretically positioned to spearhead efforts toward a carbon-neutral society, not all institutions are actively gathering and publishing data regarding their carbon footprints (Helmers

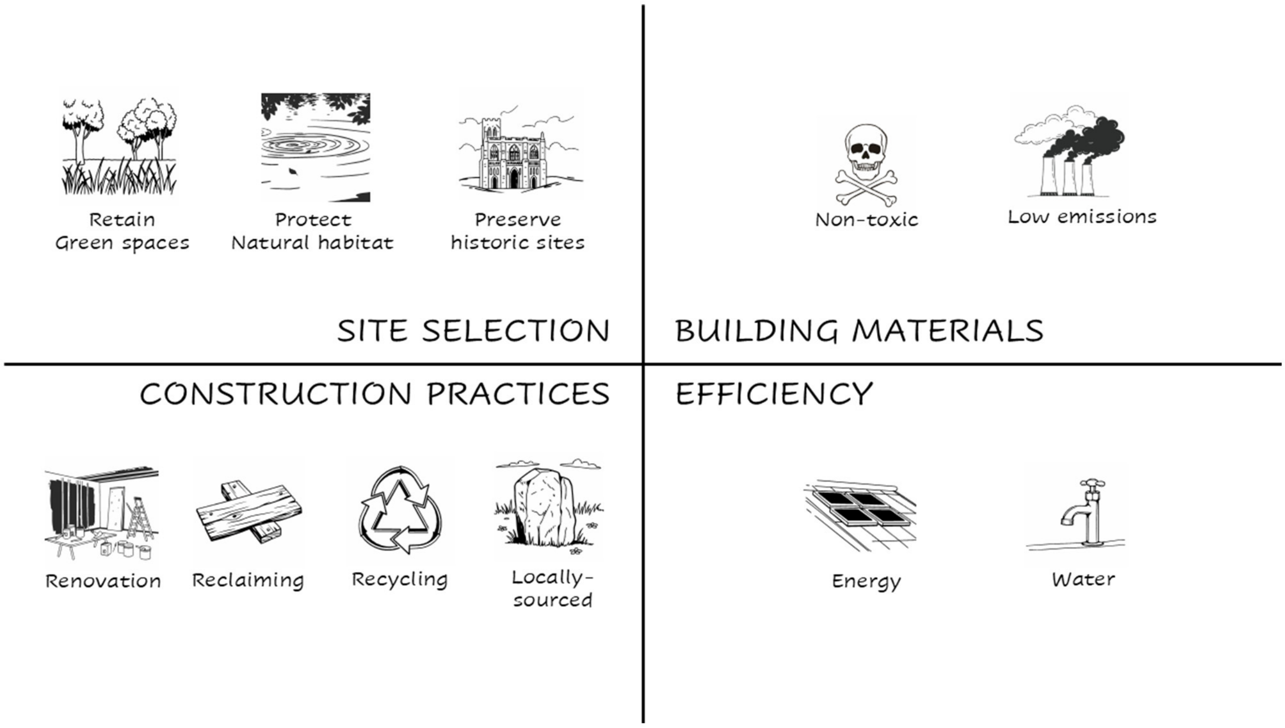

FIGURE 2
Green building practices.

et al., 2021). Nonetheless, a growing number of universities and research institutions worldwide have started to implement greener practices in their laboratories, recognizing the need to reduce their ecological footprint. Additionally, an increasing number of scientists from specific disciplines have begun to address the climate footprint of their research operations, e.g., in chemistry (Erythropel et al., 2018), neuroscience (Rae et al., 2022), computational research (Lannelongue et al., 2023), astronomy (Jahnke et al., 2020) and particle physics (Bloom et al., 2022). These initiatives have addressed various aspects of laboratory operations, ranging from the recycling and reuse of lab plasticware to the design of energy-efficient laboratories and the promotion of sustainable lab practices. These efforts represent a significant shift in the way scientific research is conducted underscoring the importance of minimizing environmental impact while continuing to advance scientific knowledge (Royal Society of Chemistry, 2022).

Numerous practices and initiatives aim to encourage the research and teaching labs of HEIs to become more environmentally friendly and sustainable, while minimizing global GHG emissions. These practices can be broadly categorized into three focus areas:

1. Reducing the energy demand and utilizing renewable energy sources wherever possible.
2. Reducing plastic usage to mitigate GHG emissions, alongside the recycling of laboratory plastics.
3. Minimizing the use of hazardous materials and producing less chemical waste to reduce environmental and human health impacts.

8.1 Lab design, energy efficiency, and resource conservation

The design of eco-friendly laboratories incorporates natural lighting, energy-efficient equipment, and advanced HVAC systems to minimize energy consumption. High air change rates for ventilation are required in laboratory buildings due to stringent indoor air quality requirements and safety regulations. This renders air-handling units the primary energy consumers, thus making them the appropriate targets for energy efficiency measures (Kitzberger et al., 2022; US EPA, and US Dept of Energy Efficiency and Renewable Energy, 2008; My Green Lab, 2023). Although lab users are not expected to redesign air handling units, they can take feasible steps, such as closing fume hood sashes, which significantly reduces energy consumption (Haugen, 2020).

The Whole Building Design Guide (WBDG Committee, 2024) provides a comprehensive outline of sustainable laboratory design, including means for improving energy and water conservation and efficiency, reducing or eliminating harmful substances and waste, and improving both the interior and exterior environments—all leading to increased productivity and the efficient use of materials and resources (Watch and Tolat, 2016; Woolliams et al., 2005). Energy-intensive lab equipment, such as autoclaves and freezers, can significantly contribute to a laboratory's environmental footprint, and consequently several studies have investigated the optimization of equipment usage and reduction of energy demand. For instance, by merely adjusting ultra-low temperature storage conditions from −80°C to −70°C, users can save 28% in energy consumption (Rae et al., 2022).

8.2 Lab plasticware recycling and reuse

Many labs produce significant amounts of plastic waste from disposable items, such as pipette tips, Petri dishes, gloves, and sample containers. In 2014, the annual plastic waste generated by biomedical labs alone amounted to ∼5.5 million tons (Urbina et al., 2015). Researchers have thus explored ways to reduce waste by recycling and/or reusing plastic labware. Some studies have investigated the feasibility and effectiveness of recycling lab plastics, while others have focused on promoting the use of reusable or biodegradable alternatives (Alves et al., 2020; Farley and Nicolet, 2023). It has been shown that operating with reusable labware as an alternative to single-use plastics can considerably reduce lab GHG emissions and potentially reduce costs (Bowler, 2022).

8.3 Green chemistry and sustainable lab practices

The concept of green chemistry, introduced ∼20 years ago, encompasses 12 principles aimed at minimizing the use of toxic materials, reducing energy consumption, and developing safer and more sustainable chemical processes that avoid or minimize the generation of hazardous substances throughout their life cycles (Anastas et al., 2000; Lane et al., 2023). Researchers have examined the applicability of integrating these principles into lab operations, alongside efforts to reduce solvents use, optimize reactions, and design more eco-friendly experiments that generate less waste. These strategies can help protect both humans and the environment from hazardous chemical exposure and production (Erythropel et al., 2018; Lane et al., 2023; Ozben and Fragão-Marques, 2023). Over 200 HEIs have signed Beyond Benign's "Green Chemistry Commitment," committing to transform chemistry education and equip future chemists with the skills to develop sustainable, efficient, and safe chemical solutions (Beyond Benign, 2025).

8.4 Challenges in green laboratories

While HEIs play a crucial role in shaping responsible graduates committed to sustainable development, the significant environmental impact of laboratories presents a challenge. Despite the growing awareness of this impact, implementing greener lab practices often faces obstacles. For instance, equipping labs with energy-efficient technologies, managing recyclable materials, and transitioning to green chemistry principles often require substantial financial investments that may exceed the resources of some institutions. Additionally, overhauling lab infrastructure and modifying established research practices pose logistical hurdles. Successfully integrating sustainable practices into laboratories demands a multifaceted approach, including securing funding, establishing efficient operational procedures, and fostering a culture of sustainability within the research community.

The journey toward sustainability in HEI's research and teaching labs is a complex process that encompasses a broad range of elements. It involves not only the transformation of physical resources, such as adopting energy-efficient equipment and recycling lab plasticware, but also the adaptation of operational procedures, such as integrating green chemistry principles and sustainable lab practices into lab management. Furthermore, this journey necessitates the development of educational programs to raise awareness and train lab personnel in sustainable practices. However, despite growing awareness, there is a lack of comprehensive data on the carbon footprint of research activities across different scientific disciplines. More research is needed to develop standardized methodologies for assessing the environmental impact of laboratory research and to promote the widespread adoption of sustainable lab practices across all scientific fields. As we move forward, ongoing research, innovation, and commitment to these domains will be pivotal in further reducing the ecological footprint of HEIs, contributing to a more sustainable future for all.

9 Eco-gardening

In HEIs, eco-gardening—for both landscaping and food production—has two major goals. The first is the assimilation of environmental education and sustainability into curricula and campus life. This objective involves the creation and maintenance of green spaces, such as gardens, plantations, or eco-gardens, where students and staff can learn about and practice ecological principles, biodiversity conservation, and organic farming (Cheang et al., 2017; Iyer-Raniga, 2022; Lau and Yang, 2009). It also aims to instill a sense of connection, responsibility, and wellbeing into the campus community and enhance its awareness of the natural environment (Iyer-Raniga, 2022). Eco-gardens provide opportunities for experiential learning, research, and community engagement in sustainability, ecology, and environmental education (Cheang et al., 2017; Duram and Williams, 2015; Lortie et al., 2022; Yuniwati et al., 2024). The second goal of eco-gardening in HEIs is to expand green areas inside and around campuses by planting and managing trees and other plants (Lau and Yang, 2009). This landscaping goal, which should be compatible with the natural environment, can improve the campus aesthetics, air quality, and microclimate (Akbari et al., 2001; Lortie et al., 2022). It should also focus on economic benefits and on how gardening of campuses can contribute to solutions for climate change adaptation in HEIs.

A study of the concept of eco-gardening within the realm of education for sustainability indicated that leveraging the perspectives of designers, educators and students (studying both environmental and non-environmental-related subjects) in the implementation of a campus eco-garden could constitute a powerful learning experience (Cheang et al., 2017). Eco-gardens can also be used as food gardens, educating students on how to grow organic food (Eugenio-Gozalbo et al., 2021; Duram and Klein, 2015; Yuniwati et al., 2024) and bringing together diverse stakeholders from the campus and the surrounding community. Furthermore, eco-gardens can serve as living laboratories for sustainability education by enabling students to engage in hands-on learning about food systems and ecological principles (Sherry, 2022). A study of 52 campuses in North America revealed that eco-gardens serve as experiential learning areas and cultivate increased environmental awareness among garden staff and students (Duram and Klein, 2015). One such enterprise is to be found at Southern Illinois University, where an environmental student group from the Department of Geography operates the Local Organic Gardening Initiative of Carbondale (LOGIC) together with stakeholders from within and beyond the University with the aim to decrease the University's carbon footprint by growing organic food for consumption on campus (Duram and Williams, 2015). Initiatives such as this usually require progressive, inclusive action involving multiple stakeholders across campus and the surrounding community (Duram and Williams, 2015). For example, the University of Portland and the Vanderbilt University have established community campus gardens—known, respectively, as SLUG (Student Led Unity Garden at The University of Portland) and VEGI (Vanderbilt Educational Garden Initiative, Vanderbilt University)—that cultivate various vegetables for student and community consumption [Association for the Advancement of Sustainability in Higher Eduction (AASHE), 2010]. An additional advantage of eco-gardens is that they can provide nutritious food and offer free or discounted produce to students, thus reducing the overall food costs for students and the university.

Additionally, gardening ecosystems within HEIs can play a crucial role in energy saving, conservation, habitat restoration, and biodiversity enhancement (Akbari, 2002; Kalicka, 2021; Lortie et al., 2022). HEIs can lead by example by implementing sustainable gardening practices, such as composting, RWH and other water conservation methods (see Section 5), and the use of native plants. Well-designed spaces on HEI campuses, such as parks, gardens, green roofs, and allotments, can help tackle climate change challenges by lowering urban temperatures, reducing flood risks, and enhancing the health and wellbeing of urban residents (Barriuso and Urbano, 2021; O'Hara et al., 2022). An illustrative example is the Orange Mall Green Infrastructure Project at the Arizona State University. The project converted an asphalt roadway into a performance-driven pedestrian mall. The landscape design incorporated a connected system of tunnels to manage stormwater runoff originating from both on-site and adjacent roadways and buildings, directing it through a series of bio-detention basins featuring native and adapted desert plants. The project integrates efficient irrigation practices with native plants to conserve water and increase local plant biodiversity, consequently attracting the unique desert fauna [Landscape Architecture Foundation (LAF), 2020].

9.1 Tree planting

Tree planting is typically implemented by HEIs as part of comprehensive programs for emission reduction. Planting trees to provide shade can conserve energy by reducing the reliance on air-conditioning. Trees can also improve air quality and mitigate the urban heat effect (Akbari et al., 2001; Griffith, 1994; Pandit and Laband, 2010). Moreover, trees play a major role in sequestering CO_2, thereby mitigating climate change (Lortie et al., 2022; Lind et al., 2023). The impact of trees on energy conservation depends on factors such as tree distribution and density and the tree species (Balogun et al., 2014; Zhang et al., 2018). Two examples of tree planting on campuses are presented below.

Greifswald University (Germany) undertook tree planting as part of an extensive program aimed at reducing CO_2 emissions (Udas et al., 2018). The program focused on three main strategies to offset the University's carbon footprint: (1) Implementing measures to reduce CO_2 emissions through technological advancements and behavioral modifications; (2) implementing measures to offset unavoidable CO_2 emissions by increasing carbon sequestration on university-owned forest lands; and (3) mainstreaming sustainable practices through teaching and research. Similarly, NED University (Karachi, Pakistan) also invested in tree planting initiatives on campus and participated in forestation projects in urban areas as part of its efforts toward achieving a carbon-neutral campus. NED University's primary strategies for mitigating carbon emissions were plantings both inside and outside campus, alongside transitioning to renewable energy sources to meet its power requirements. These strategies were accompanied by outreach activities targeted at the University's community and other stakeholders and focused on practices to reduce the University's carbon footprint (Mustafa et al., 2022). Both Greifswald and NED Universities used an accounts assessment, converting all outcomes to units of tons of CO_2 emissions.

9.2 Challenges in vegetation and gardening

The gardening challenges facing HEIs might include: limited funding and resources; space constraints (especially in urban campuses); climate and soil conditions that limit the types of vegetation suitable for these purposes and hence requiring careful selection of plant species; maintaining a diverse range of plant species; effective engagement strategies encouraging student and staff participation in gardening initiatives; availability of the specialized knowledge required for implementing sustainable gardening practices; aligning gardening projects with educational goals and curricula; and establishing a long-term planning vision for campus greenery that aligns with the institution's sustainability goals. These challenges highlight the need for comprehensive planning and cooperation among various participants within HEIs toward successfully sustaining campus vegetation and gardening efforts (Leal Filho et al., 2020).

10 Discussion

The aim of this review was to highlight the main current approaches for promoting green practices on HEI campuses, identify the challenges to their implementation and suggest strategies for overcoming them. To this end, we surveyed over 180 scientific studies and reports as well as numerous initiatives from around the world. The main conclusion of this review is that there is no consensus on the key components required for a sustainable institution: While sustainability encompasses three pillars—environment, economy, and society—most sustainability initiatives predominately emphasize the environmental pillar.

The second, and perhaps the most important conclusion, is the need for global standardization for green campuses. In some cases, this absence of global standards leads to greenwashing, with HEIs declaring "sustainability goals" as a means of self-promotion, with no critique or sanction system in place in the case of failure to achieve these goals (Mohammadalizadehkorde and Weaver, 2018).

The lack of clarity regarding the key components required for a sustainable institution and the absence of global standardization for green campuses were noticeable in many of the reviewed fields. For example, there are currently no internationally adopted guidelines for calculating carbon footprint in HEIs, and institutions thus utilize diverse methods to perform their GHG calculations (Mustafa et al., 2022). Similarly, there are no global standards for waste and runoff management, water and energy conservation, RWH, renewable energy production systems, the design and operation of green labs, and gardening and tree planting policies. Green buildings are an exception. Certifications and rating systems for green buildings have been established by several countries, including the American LEED certification (U.S. Green Building Council, 2016), the IL5281 Green Building Standard Certification, the popular UK Building Research Establishment Environmental Assessment Method (BREEAM) certification, and the Australian Green Star. Nevertheless, it is important to emphasize the key role of state-level or regional directives and regulations, such as the EU minimum efficiency performance standards and labeling for lighting and office equipment, which has had a significant effect on electricity demand in university buildings (Fonseca et al., 2018; Lee and Lee, 2021). Such region-wide directives highlight the critical role of mandatory national and international standards for HEI green campus initiatives.

To overcome standardization barriers, several international (e.g., the Association for the Advancement of Sustainability in Higher Education) and national (e.g., Green-Campus Ireland) programs have been established. Expanding and mandating the use of these initiatives or other global HEI green campuses initiatives standards is a vital need.

10.1 Challenges in implementing sustainability in HEIs

There are many challenges to implementing sustainability in HEIs. Some of the challenges are general, like the need for funding or leadership. Other challenges are content-specific, and include integrating green chemistry principles and sustainable lab practices into lab management, the integration of water and runoff management practices into curricular and research activities and addressing the lack of internationally-adopted guidelines for calculating carbon footprints in HEIs.

Funding—Achieving energy and water efficiency, managing campus runoff and waste, and reducing GHG emissions can pose considerable challenges, since a large-scale infrastructure, involving significant costs, needs to be constructed and maintained.

Leadership—A lack of commitment from university administrations is one of the major obstacles to promoting green and sustainable campuses (Amaral et al., 2020). Such a commitment is pivotal for prioritizing budget allocations and promoting educational programs (Leal Filho et al., 2019). One of the reasons for this lack of commitment is a lack of understanding of the environmental and economic benefits of campus sustainability initiatives (Horhota et al., 2014). Ignorance concerning the benefits of campus sustainability can also create resistance to change. These factors can cause major setbacks in integrating green building and green lab practices into HEIs that already have initiatives in place for less-intensive water and energy consumption, reduced GHG emissions, renewable energy production on campus, and waste, gardening, and runoff management. These challenges might also cause resistance and insufficient funding for promoting individual initiatives in HEIs where designing and constructing green buildings or conducting a comprehensive green renovation are economically unfeasible.

Commitment on behalf of staff and students—Several studies have highlighted the need for ongoing campus community engagement and the critical role of behavioral change among members of the campus community (Mustafa et al., 2022; Rebelatto et al., 2019; Soares et al., 2015; Udas et al., 2018). Cultivating a long-term behavioral change toward energy and water efficiency and individual carbon footprint is essential. Effective engagement strategies that encourage student and staff participation in campus gardening initiatives, waste reduction, recycling programs and field runoff management are crucial for the success of these projects. Other common barriers are a lack of interest and expertise (Amaral et al., 2020).

10.2 Overcoming challenges in sustainability implementation in HEIs

Many of the above challenges can be addressed by strategic campus planning (including infrastructure and funding), providing financial incentives to faculty and staff members, assessing student perceptions, encouraging knowledge acquisition, appointing a campus sustainability officer, and promoting a wide range of green initiatives. Educating and engaging all campus stakeholders is essential for raising awareness about sustainability and for driving behavioral changes (Debrah et al., 2021). Overcoming the challenges requires a collaborative multidisciplinary approach that involves all campus stakeholders in the planning and implementation of green campus management initiatives. As we move forward toward sustainability, the integration of campus resource management practices into curricular and research activities can further enhance the educational mission of HEIs. Multidisciplinary research and innovation will be pivotal contributors to a more sustainable future by preparing future leaders to properly address humanity's growing ecological and carbon footprints and future global climate change and sustainability challenges.

10.3 Strengths and weaknesses

The strength of this comprehensive review stems from the perspectives provided by an extensive body of scientific literature including studies, scientific reports, and initiatives around the world. Due to size limitations in this publication, campus social and economic sustainability aspects will be discussed in a complementary review on social sustainability, education, transportation, health, economy and marketing. However, given the broad scope of this research, some studies, initiatives and insights may have been inadvertently omitted from the review. Despite these limitations, the uniqueness of this literature review lies in its broad global scope, its comprehensive coverage of various fields within the green campus initiatives, and its examination of the diverse types of literature and initiatives.

11 Conclusions and recommendations

The global climate change crisis, coupled with the ongoing global pollution crisis and the predicted anthropogenic sixth extinction event, makes it immediately necessary for countries and their institutions worldwide to profoundly change their actions. If clearly defined mitigation and adaptation measures are not put in place, there could be severe consequences for human life, infrastructure, and the economy. HEIs are in a unique position to lead this change because they have intellectual and practical resources. They not only generate knowledge and technologies for sustainability, but they also educate future generations who will deal with this critical moment. HEIs can be living laboratories by showcasing sustainable practices across their operations, from energy and water conservation to waste reduction. Their influence reaches beyond campus borders and inspires other institutions and corporations to practice environmental stewardship. Despite existing challenges, a multidisciplinary approach, strong leadership, and dedicated funding can create a greener future. Furthermore, by prioritizing both environmental and social aspects of sustainability, universities can empower disadvantaged populations and foster public awareness, helping to build a more resilient society.

There is no consensus on the key components of a sustainable institution. Most sustainability initiatives emphasize the environmental pillar, although sustainability incorporates three pillars: environment, economy, and society. This lack of clarity has been noticeable in many areas of sustainability, including a lack of internationally adopted guidelines for calculating carbon footprints and no global standards for waste and runoff management, water and energy consumption, and eco-gardening (Mustafa et al., 2022).The absence of global standards has also led to greenwashing, where HEIs state "sustainability goals" to promote themselves without critique or sanctions if they fail to reach these goals (Mustafa et al., 2022).

To achieve campus sustainability, HEIs should establish a dedicated Sustainability Office to coordinate efforts, develop a comprehensive plan, and set measurable goals. This office would oversee the implementation of environmental initiatives, including energy and water conservation, waste reduction, green laboratories, and eco-gardening projects. Engaging stakeholders through education and participation in sustainability programs is crucial for fostering behavioral changes. Integrating sustainability into academics through curriculum development and multidisciplinary research is essential for preparing future leaders. Institutions should adopt standardized practices for carbon footprint calculation and resource management while ensuring strong leadership support in institutional strategic programs and individual initiatives. Collaboration across disciplines and innovation in addressing sustainability challenges are key, as is extending the impact beyond campus borders to inspire broader environmental stewardship. By taking these actions, HEIs can become living laboratories for sustainability, contributing significantly to global efforts in combating climate change, pollution, and biodiversity loss.

Author contributions

ZB-I: Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. ST: Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. DB: Investigation, Writing – original draft. TA: Investigation, Writing – original draft. AD: Investigation, Writing – original draft. GC: Investigation, Writing – original draft. AL: Validation, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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