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Organizational life cycle assessment of Kabul University: evaluating environmental sustainability in a post-conflict higher education institution

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Abstract

The study conducted an Organizational Life Cycle Assessment (O-LCA) of Kabul University to evaluate its environmental impacts and sustainability practices in post-conflict Afghanistan's context. There is limited empirical evidence applying O-LCA to examine universities in a post-conflict context, where distinct infrastructural, resource, and data barriers persist. The sustainability practices evaluated include energy efficiency initiatives, the adoption of green building techniques, waste reduction and management, and the incorporation of environmental sustainability into university curricula, all aimed at minimizing the environmental footprint and improving resource efficiency at Kabul University. The research applied the O-LCA method in accordance with the ISO/TS 14072 standard, utilizing the ReCiPe 2016 impact assessment method. The data from the 2020 academic year across key operational areas, including energy use, water consumption, waste generation, and transportation, were analyzed. The results indicate that Kabul University's main sources of environmental impact are electricity consumption (45.7%), transportation (24%), and building operations (19.4%). The adverse effects are predominantly found in the categories of human health and resource depletion, while impacts on ecosystems are notably less pronounced. Consequently, the O-LCA results emphasize the critical need for Kabul University to address its environmental impacts, particularly in the domains of air pollution, greenhouse gas emissions, and resource depletion. Additionally, this research provides valuable insights for university administrators, policymakers, and stakeholders in Afghanistan and other post-conflict regions seeking to enhance the environmental sustainability of higher education institutions. The findings are applicable to other higher education institutions in post-conflict settings. Pathways for future research include more robust data collection, longitudinal environmental performance tracking, and broader methodological application across diverse post-conflict settings. These initiatives align with multiple United Nations Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).



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Keywords Organizational life cycle assessment, Post-conflict sustainability, Environmental impact assessment, Higher education in Afghanistan, Electricity consumption

1 Introduction

In September 2015, with the adoption of 17 Sustainable Development Goals (SDGs), the United Nations (UN) reaffirmed the urgent need to conserve natural resources and the environment [57, 65]. Building upon this global agenda, it is equally important to understand how sustainability challenges manifest at regional and national levels, particularly in countries affected by conflict and limited resources, such as Afghanistan. The global agenda emphasizes that challenges such as climate change, water scarcity, and resource depletion limit sustainable development [39].

Afghanistan is a landlocked country in South-Central Asia, bordered by Iran, Pakistan, Tajikistan, China, Uzbekistan, and Turkmenistan. It covers a geographic area of approximately 652,870 km² and supports a population exceeding 40 million [73]. Decades of conflict have severely impacted Afghanistan's infrastructure and socioeconomic development [48]. Within this challenging context, Afghan universities increasingly recognize the need to integrate sustainability into campus operations and curricula [8, 47]. To examine how Higher Education Institutions (HEIs) can contribute to environmental sustainability, it is first necessary to review existing tools and frameworks that measure organizational sustainability.

As a signatory to the United Nations 2030 Agenda, Afghanistan is committed to achieving all 17 SDGs within its national policy and statistical reporting framework. Afghanistan frequently submits indicator data across all main SDG sectors, such as health, education, clean water and sanitation, affordable and clean energy, reduced inequalities, and climate action. The profile details national progress, achievements, and ongoing challenges in implementing SDGs 1–17, highlighting the government's commitment to multisector sustainable development despite considerable constant social and economic limitations [64].

HEIs in developing countries, especially those in post-conflict settings, face distinct and intricate sustainability challenges. These challenges are often worsened by limited resources, damaged infrastructure, and the need to rebuild social and educational systems [8]. Universities in Afghanistan are also facing problems and challenges, such as the need for faculty development and quality assurance [47]. These complex issues must be addressed in the struggle to rebuild and reform higher education in the country while aiming for sustainability [9].

Universities in Afghanistan face sustainability problems and issues similar to those encountered by other post-conflict countries in the region. For example, universities in Iraq struggle with retaining academic staff, rehabilitating infrastructure, and modernizing courses to fulfill the demands [6]. Syrian universities also face similar challenges in terms of rebuilding classrooms, dealing with the loss of qualified faculty, and reintegrating displaced students [70].

The common issues of scarce resources and damaged infrastructure have a substantial impact on sustainability initiatives in post-conflict environments. These factors hinder universities in Afghanistan, Iraq, and Syria from adopting sustainable practices, highlighting the need for focused interventions that address resource constraints,

infrastructure development, and capacity building [47]. Afghanistan is a post-conflict country that faces regime changes and political instability. The limited availability of facilities and resources for higher education in provinces and remote regions directly and indirectly affects girls' access to higher education in Afghanistan. Furthermore, access to education in developing countries has been hindered by various influential factors, such as severe poverty, violent conflicts, natural disasters, and other challenges [4, 5].

In the context of Afghanistan, research on higher education primarily focuses on institutional capacity, academic policy reforms, and access [56, 72]. However, there is a lack of documented empirical studies utilizing O-LCA in public universities or HEIs within post-conflict environments. This indicates a contextual gap concerning post-conflict, developing nation HEIs and a methodological gap in the application of O-LCA within these institutions. This study aims to fill these gaps by applying the O-LCA framework (ISO/TS 14072) to assess the environmental performance of Kabul University, the largest public university in Afghanistan.

Higher education institutions play a vital role in promoting peacebuilding and social reconstruction in areas affected by conflict. They function as centers for the creation of knowledge, enhancement of skills, and promotion of social unity. Nevertheless, these establishments frequently encounter challenges, such as insufficient financial resources, loss of talented individuals, obsolete educational programs, and inadequate research capacities [7].

The O-LCA of Kabul University highlights sustainability issues in higher education in Afghanistan, particularly at Kabul University. This study analyzes the environmental input and output of resources and the impact assessment of the whole education process, as well as recommends a suitable solution for the environmental impacts generated by HEIs. Kabul University, like other HEIs, aligns with the UN SDGs, including SDG 3 (Good Health and Well-Being), SDG 4 (Quality Education), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Production and Consumption), and SDG 13 (Climate Action). These aspects are evaluated in the Organizational Life Cycle Sustainability Assessment (OLCSA) study, and the findings will contribute to the achievement of these SDGs. The goal of SDG 4 is to provide equitable and high-quality education, and HEIs/universities are recognized as key actors in accomplishing the SDGs. Furthermore, institutions of higher education and universities are reorienting their practices and policies to promote education that allows the existing generation to dedicate itself to a sustainable and supportable life [46].

Additionally, Kabul University faces difficulties in implementing sustainability initiatives due to Afghanistan's post-conflict environment. Sustainable design principles can be incorporated into the university's ongoing efforts to rebuild and modernize its facilities [4, 5]. Kabul University has a unique opportunity to lead in this area despite facing significant challenges in implementing sustainability initiatives due to its historical significance and central role in Afghan higher education. The university can significantly contribute to sustainability in Afghanistan's higher education sector and beyond by addressing its weaknesses and utilizing its strengths [58].

The natural environment faces numerous challenges, including air pollution, water contamination, soil degradation, and climate change. Higher education institutions are crucial in addressing these challenges via education, research, and sustainable practices.

However, HEIs in post-conflict environments encounter distinct sustainability issues that are intensified by resource limitations and damaged infrastructure.

Despite the increasing adoption of O-LCA in developed countries such as Spain and Germany, there remains a notable absence of empirical O-LCA applications in post-conflict and data-scarce HEIs. Methodological challenges, such as incomplete LCA data, limited environmental reporting systems, and infrastructure constraints, further hinder the use of O-LCA in the developing context. Moreover, previous studies have rarely compared results across universities operating under contrasting conditions of stability and resource availability. Consequently, the research gap lies in demonstrating how O-LCA can be adopted and applied to evaluate environmental impacts under such constraints. Addressing this gap, while providing both methodological insights and policy relevance, presents a challenge in a fragile education system like Afghanistan's.

This study applies the O-LCA framework to quantify and evaluate the environmental impact of Kabul University as a representative post-conflict HEI. The research aims to identify key environmental hotspots, particularly energy, water, waste, and transportation, and to demonstrate how O-LCA can be effectively implemented in the post-conflict context, such as Afghanistan. Therefore, the central research question guiding this study is: How can O-LCA be effectively applied to assess and improve the environmental performance of an Afghan HEI? Having outlined the purpose of this study and its guiding question, the following points summarize its main contributions to both methodology and practice: (i) presenting the first empirical O-LCA of an Afghan University, (ii) offering a context-specific adaptation of ISO/TS 14072 suitable for organizations with limited data in post-conflict environments, and (iii) providing policy-relevant insights to guide sustainability strategies for universities in Afghanistan and comparable developing regions. To situate this study within existing knowledge, the following section reviews previous O-LCA applications and highlights key research gaps.

1.1 Literature review and research gaps

Over the last 20 years, Life Cycle Assessment (LCA) has become a fundamental tool for measuring environmental impacts across various sectors, including industry, energy, infrastructure, and services [27]. The transition from product-level LCA to organizational-level evaluation has resulted in the development of O-LCA, formalized in ISO/TS 14072 [30] and endorsed by the United Nations Environment Program/Society of Environmental Toxicology and Chemistry (UNEP/SETAC) Guidance on O-LCA [63]. Organizational life cycle assessment allows institutions to monitor comprehensive resource flows and environmental impacts throughout their lifecycle at the organizational level [43, 51].

The implementation of LCA, particularly O-LCA, in the global higher education sector is still in its early stages. Lo-Iacono-Ferreira et al. [36] discovered significant obstacles in delineating boundaries, obtaining data, and interpreting results in the context of HEIs. A systematic review conducted by Wafa et al. [68] and Viere et al. [66] further emphasized that O-LCA research in HEIs remains limited globally. Moreover, in Asia, particularly in emerging and post-conflict countries, O-LCA studies in HEIs remain scarce [16, 56].

According to ISO/TS 14072 [30], organizational LCA, or O-LCA, is the process of collecting and evaluating the inputs, outputs, and possible environmental impacts of an

organization's activities [30], UNEP/SETAC,). Additionally, O-LCA is a life cycle strategy for addressing an organization's environmental footprint. By considering stakeholder interests, the O-LCA method identifies and measures environmental concerns that extend beyond the organization's borders. It is an environmental impact assessment strategy that analyzes the environmental concerns that are significant to an organization and provides a profile of the potential environmental impact of its operations [36].

Specifically, ISO/TS 14072 [30] emphasizes the identification, assessment, and interpretation of environmental factors that potentially affect organizations [28]. Although O-LCA is still a relatively new concept, researchers and managers have been applying an LCA perspective to evaluate the environmental performance of organizations for some time [21, 36].

The O-LCA Guidance, which aligns with ISO/TS 14072 [30], demonstrates how this technique can be applied and assists professionals in overcoming methodological challenges that arise when shifting their focus from products to organizations [41]. Although Lo-Iacono-Ferreira et al. [36] applied the O-LCA study within an HEI combined with the environmental management system (EMS), there are no studies focusing exclusively on the O-LCA of universities.

ISO 14001 [28], known in Europe as the Eco-Management and Audit Scheme (EMAS), serves as a guide for many organizations seeking certification for their EMSs. These frameworks primarily assist with procedural compliance and when incorporating an organization into an eco-balance assessment, the frameworks typically focus on operational processes from gate to gate. The International Organization for Standardization developed ISO/TS 14072 [30]. The majority of ISO 14044 [29] standards (27 out of 31) fundamentally address products to organizations. In addition, along with the creation of the standard document, UNEP/SETAC Life Cycle Initiative launched the flagship project LCA of organizations, which evaluates the capabilities and applications of LCA in organizations [63].

Moreover, ISO/TS 14072 serves as the foundation for O-LCA, and the guidance complies with this standard [43]. Numerous studies have utilized the Guidance on Organizational Life Cycle Assessment.

Furthermore, O-LCA can be used to evaluate an organization's environmental performance and the benefits associated with its decision-making processes, as the technology can generate the necessary data. Key advantages of O-LCA implementation include the provision of advisory reports and transparent policies [36, 68]. Environmental impact profiles provide essential information for organizational decision-making to disclose environmental insights [63]. Martínez-Blanco et al. [43] demonstrated that O-LCA can be utilized to anticipate scenarios and drive data-collection programs. Consumption of energy, water, and land, as well as waste generation and contributions to climate change, as identified by [35, 36], are primary categories that are likely influenced by the availability of educational facilities.

The UNEP/SETAC 2015 guideline was developed with consideration of ISO/TS 14072. In their study's conclusion, Lo-Iacono-Ferreira et al. [36] made several recommendations. Thus, the O-LCA methodology is relevant to HEIs. The O-LCA Guidance, which is aligned with ISO/TS 14072 [30], demonstrates the applicability of the technique and assists professionals in overcoming methodological challenges associated with shifting their focus from products to organizations [41]. Although Lo-Iacono-Ferreira et al. [36]

applied the O-LCA study in HEIs combined with the EMS, no studies have been found that address university O-LCA separately.

There is no specific evaluation available on the O-LCA of HEIs in post-conflict settings. A literature review was conducted to examine the current methods used to ecologically assess HEIs. The review aimed to identify the methodological approaches employed, the activities evaluated, and the environmental impacts assessed by HEIs. Publications that conducted environmental assessments of an HEI, campus, or faculty were identified. Assessments that evaluated greenhouse gas (GHG) emissions and, ideally, a broader range of environmental impacts, were considered [31].

The methodology for conducting LCA on HEIs is discussed based on the framework outlined in ISO/TS 14072 and insights from the literature review. Figure 1 illustrates the approach, which is outlined according to the ISO/TS 14072 and encompasses relevant aspects.

The minimum environmental impacts associated with providing educational services at Kabul University are land use, fuel consumption, water use, and waste generation. To study indirect emissions and resource consumption, primary data are required to calculate direct emissions and resource use [36]. It is the responsibility of organizations to

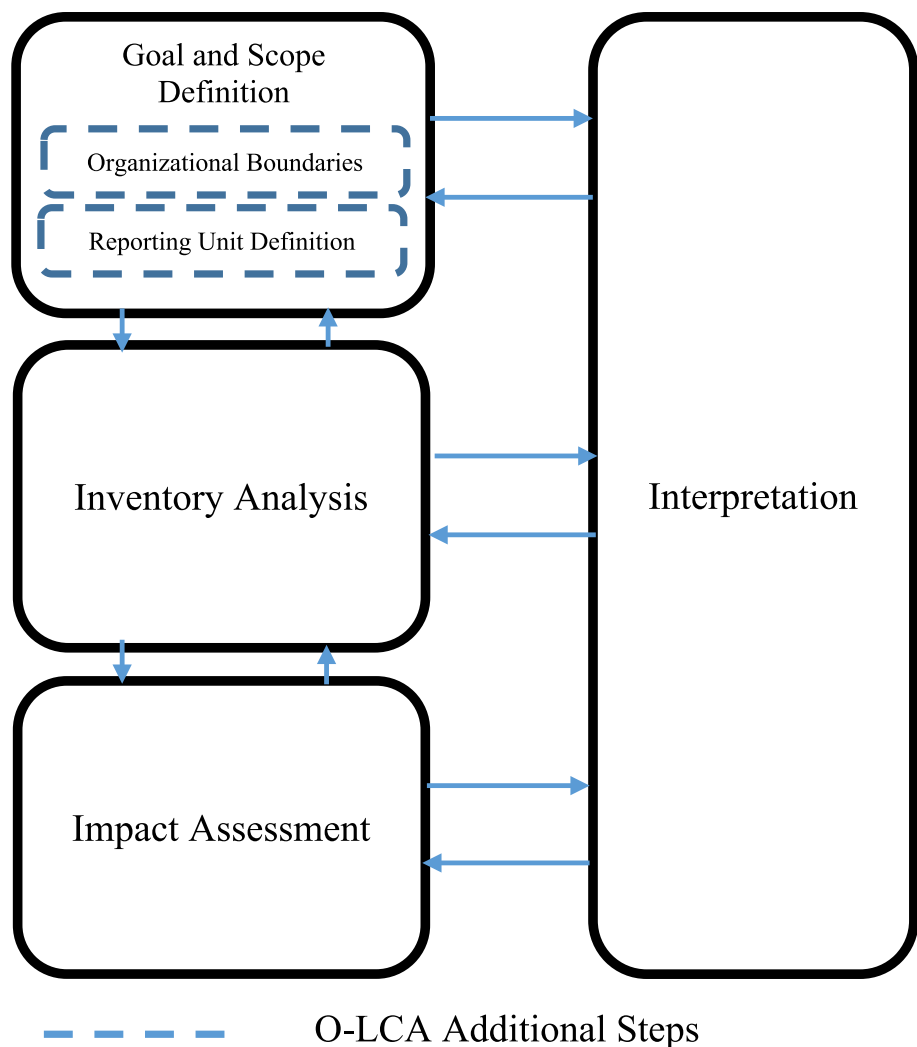


Fig. 1 A combined structure of O-LCA and LCA [39]

collect quality data to ensure that the inventory reflects the state of their organization in an appropriate way [63]. Addressing these methodological and contextual gaps provides the conceptual foundation for the current study, which applies the O-LCA framework to Kabul University.

1.2 Overview of O-LCA application in HEIs using systematic literature review

To ensure the reproducibility and transparency of the systematic literature review, the full search protocol and Boolean search string used in Scopus are presented as follows. The search strategy combined keywords related to organizational sustainability assessments with those specific to HEIs. The final search string applied was: ("Organizational Life Cycle Assessment" OR "Organizational LCA" OR "OLCA" OR "O-LCA" OR "Life Cycle Assessment of Higher Education Institutions") AND ("Higher Education" OR "Higher Education Institution" OR "education" OR "university" OR "campus" OR "suitability for higher education institutions"). The results are summarized in Table 1 accordingly.

The reviewed studies collectively validate the gradual progression of O-LCA and its extensions in the higher education sector. Early methodological contributions, such as Lo-Iacono-Ferreira et al. [36], assessed the suitability of O-LCA for universities with established EMSs, while Bueno et al. [10, 11] and Erauskin-Tolosa et al. [19] extended this application to evaluate the environmental and social footprints of the University of the Basque Country. These studies demonstrate how O-LCA and Organizational Life Cycle Assessment (SO-LCA) frameworks can be integrated into institutional sustainability management using standardized tools such as ISO/TS 14072 and the UNEP/SETAC guidelines. Collectively, they highlight the cumulative importance of integrating environmental and social indicators to comprehensively assess the sustainability performance of HEIs.

Harmonizing the findings of Deda et al. [17] and Wafa et al. [68] reveals the increasing scientific interest in O-LCA-based sustainability assessments through bibliometric and systematic review methods, providing a global overview of trends, research gaps, and methodological limitations. Studies such as Cooney et al. [15] cover the framework's scope beyond institutional boundaries by measuring research-related and social impact pathways, while Sining et al. [61] explore social well-being at the student level. Despite methodological variety, all studies agree that O-LCA and its derivatives (SO-LCA and OLCSA) offer a robust, though still developing, approach for measuring the sustainability performance of HEIs. Common challenges include inadequate data availability, system boundary discrepancies, and the need for consistent indicators to improve comparability across organizations.

1.3 O-LCA method selection in higher education studies

Recent O-LCA of HEIs have highlighted diverse methodological approaches contingent on institutional context and data availability. For instance, Jürgens et al. [31] proposed a structured O-LCA framework piloted at a German university, integrating both primary and secondary data sources to assess environmental aspects across organizational units. Their study is situated in a technologically advanced institutional setting with access to digitalized environmental metrics.

Table 1 Summary of key studies applying O-LCA and related approaches to HEIs

Author	Title	Objective	Method	Country	Limitations
Bueno et al. [11]	The Environmental and Social Footprint of the University of the Basque Country UPV/EHU	To calculate the environmental and social footprint of an HEI	Life cycle inventory using databases (Ecoinvent 3.3) and modeling	Spain (Basque Country)	Case study of an HEI; may not be broadly generalizable
Bueno et al. [10]	Dataset on the Environmental and Social Footprint of the University of the Basque Country UPV/EHU	To provide a dataset on the environmental and social footprint of an HEI	Data in a brief compilation of LCA/SO-LCA flows for the HEI	Spain (Basque Country)	No full analysis; information beyond the institution is limited
Chang et al. [12]	Application Options of the Sustainable Child Development Index (SCDI): Assessing the Status of SD and Establishing Social Impact Pathways	To propose application options for the SCDI, including its integration in S-LCA and SO-LCA	Secondary analysis/ conceptual development; an example application of SCDI	Germany (TU Berlin)	Not specifically focused on HEIs; thus, its applicability may be limited
Cooney et al. [15]	Accounting for Research-Induced Environmental Impacts Using Life Cycle Assessment	Estimate the environmental impact of a research project and apply O-LCA as a decision-making tool	Case study of O-LCA applied to a research project; scenario modeling of alternative behaviors	Ireland (University of Galway)	The focus is on a research project rather than an HEI; does not cover all organizations
Deda et al. [17]	Bibliometric Analysis and Benchmarking of Life Cycle Assessment of Higher Education Institutions	Perform a bibliometric analysis and benchmarking study of LCA adoption in HEIs	Bibliometric review and benchmarking of literature; analysis of trends, barriers, and scopes	Portugal (University of Coimbra)	No primary case study; relies on availability and consistency
Erauskin-Tolosa et al. [19]	Social Organisational LCA for the Academic Activity of the University of the Basque Country UPV/EHU	Estimate the social footprint of an HEI based from an LCA perspective	SO-LCA of an HEI; stakeholder impacts using databases	Spain (Basque Country)	Data availability for social impacts is challenging
Lo-lacono-Ferreira et al. [36]	Organizational Life Cycle Assessment: Suitability for Higher Education Institutions with Environmental Management Systems	Analyze the suitability of the O-LCA for the HEI with EMS verification	Pilot case of O-LCA applied to the HEI with EMS; ISO/TS 14072 and UNEP Guidance	Spain (UPV)	The focus is on HEIs and EMS; not generalized; pilot unit only
Sining et al. [61]	A Study of Social Well-Being Among University Students	Study the social well-being of university students using sustainability indicators	Empirical survey of student social well-being (linked to LCA discourse)	Not specified	Not directly an O-LCA case for the HEI; student-focused
Wafa et al. [68]	Organizational Life Cycle Sustainability Assessment (OLCSA) for a Higher Education Institution as an Organization: A Systematic Review and Bibliometric Analysis	Systematically review and perform a bibliometric analysis of OLCSA/ HEI organizational studies worldwide	Systematic literature review (PRISMA) and bibliometric analysis of OLCSA/ HEI literature	Global, multiple countries	Review only; not a primary empirical case study

Bueno et al. [11] conducted a comprehensive O-LCA and SO-LCA for the University of the Basque Country in Spain, encompassing social impacts and hypothetical commuting scenarios. The study benefited from collaboration with utility providers and used Ecoinvent datasets to supplement on-campus data.

Lo-Iacono-Ferreira et al. [36] examined the integration of O-LCA within an EMAS-certified EMS at a Spanish university, demonstrating the compatibility of LCA tools with institutional sustainability contexts.

In contrast, the current study at Kabul University adopts a gate-to-gate approach tailored to a post-conflict context, where institutional infrastructure, monitoring tools, and digital data systems are limited. Unlike previous studies conducted in well-resourced settings, Kabul University faces different challenges, such as generator-based power, disorganized transport records, and minimal waste tracking systems. Therefore, the methodology highlights the use of proxy data, expert triangulation, and boundary setting, highlighting how O-LCA can be adapted for fragile or resource-limited educational environments.

1.4 Methodology

The study adopts the ISO/TS 14072 [30] O-LCA methodology to suit the unique post-conflict operational context of Kabul University. Rather than following a generic procedural outline, the methodology reflects critical decisions made to overcome specific local barriers, such as the lack of digital infrastructure, reliance on fuel-based energy sources, and limited transport documentation. Each step of the O-LCA, from defining the system boundary to impact assessment, was revised to align with KU's limited institutional capacity and resource constraints. The contextualized approach offers practical lessons for applying O-LCA in fragile or conflict-affected regions. Furthermore, each subsection describes the specific method, data sources, and assumptions applied to ensure clarity, transparency, and scientific reproducibility of the O-LCA conducted for Kabul University.

1.5 Site selection

Kabul University was selected as the organizational unit for this O-LCA study because it is the largest and oldest public HEI in Afghanistan. Kabul University serves as a central node in the national education system, is directly managed by the Ministry of Higher Education (MoHE), and therefore reflects the structure and resource profile typical of public universities in the country [8].

The selection of Kabul University provides a representative case for assessing the environmental performance of Afghanistan's higher education sector for three reasons: (i) In terms of scale and representation, Kabul University's extensive campus, diverse activities, and multiple service facilities generate comprehensive environmental flows (energy, water, waste, and transportation) comparable to those of other national universities. (ii) Considering the post-conflict context, Kabul University operates with limited infrastructure [8, 47], offering a realistic test case for adopting the O-LCA method to developing post-conflict institutions. (iii) Policy and demonstration relevance are crucial; as a flagship public university, Kabul University's sustainability evaluation can inform the MoHE policy decisions and serve as a replicable model for other Afghan HEIs.

In addition to Kabul University's scale and centrality, the selection was influenced by its representativeness of the operational limitations common across Afghan HEIs. For example, the campus lacks smart meters for automated resource monitoring, resulting in reliance on manually logged data and departmental estimations. These limitations

informed several methodological adjustments throughout the study, including proxy data calibration and adopted data collection flows.

Kabul city is the capital of Afghanistan's located in the eastern part of the country at 34°31' N and 69°12' E, 1,800 m above sea level [69]. The study area covers all operational activities within the main Kabul University campus, located in District 3 of Kabul City (34° 30' N, 69° 09' E), including academic buildings, laboratories, dormitories, administrative offices, and common facilities. These boundaries capture the main life cycle flows of electricity, fuel, water, solid waste, and transportation, which reflect the university's environmental footprint [31, 36].

1.6 Organizational life cycle assessment

The O-LCA framework was applied to evaluate the environmental performance of Kabul University, following the principles of ISO/TS 14072 [30] and UNEP/SETAC [63] Guidance. The methodology was structured into four classical LCA phases: goal and scope definition, inventory analysis, impact assessment, and interpretation, adapted to the organizational scale of a university. Figure 1 presents the overall workflow used in this study, which consists of four main phases. Each phase is described in detail in the following sections.

The motivation behind O-LCA is to ensure meaningful performance tracking. Performance tracking, a promising application of O-LCA, involves the continuous evaluation of an organization's environmental performance over time to determine its rate of improvement [40]. As previously noted, the O-LCA method is developed based on ISO/TS 14072. Additional international reference guidance and reports that provide greater depth in the implementation of LCA and organizational value chain techniques can also help with phases that have not been thoroughly explained [63].

Implementing O-LCA in universities, particularly in the specific circumstances of a developing country like Afghanistan, presents distinct and specific difficulties. Universities are complex establishments engaged in diverse activities, including teaching, research, and administrative tasks. It is crucial to clearly define system boundaries and functional units for each activity, as they have unique environmental implications [36]. Besides, O-LCA can be used by organizations of all sizes and types to identify opportunities for environmental improvement and to demonstrate a commitment to sustainability.

1.6.1 Definition of goal and scope

Organizational life cycle assessment is a tool used to evaluate the environmental impacts of an organization over its entire lifespan, encompassing raw material extraction, production, distribution, use, and end-of-life disposal [43]. This O-LCA study aims to evaluate the environmental impacts associated with Kabul University as an HEI in Afghanistan during the reference year 2020.

The goal of an HEI's O-LCA should be to help the institution monitor and improve its performance. Additionally, it should be utilized to report the HEI's environmental impact over a specified time period [31]. The goal of this O-LCA study is to evaluate the environmental impacts of Kabul University as an HEI in Afghanistan. Kabul University is the largest and oldest university in Afghanistan, hosting approximately 24,633 students and 1,214 academic and administrative staff, and offering 103 degree programs across 21 faculties. Kabul University is active in both teaching and research, covering social

sciences (economics, political, public policy, literature, and Islamic sharia and law) and natural sciences (engineering, science, environment, and veterinary science).

The scope of this O-LCA includes assessing complex implications within higher education systems while maintaining alignment with societal needs for sustainability. In summary, the goal and scope define the analytical boundaries, data reference period, and reporting unit of the study, while providing a detailed contextual profile of Kabul University as the study site.

1.6.2 Reporting organization

Although it is possible to evaluate only a few schools or campuses at an HEI, it is preferable to assess the entire institution to gain a comprehensive understanding of its environmental impacts [31]. This approach ensures that all activities are collectively accountable rather than allowing accountability to be diverted across departments. Kabul University is the reporting organization for this assessment. The reference period, which is often a calendar year, must be specified in the LCA. Institutions of higher learning may consider implementing an academic calendar with separate semesters for winter and summer. Statistics from several HEIs are available for a single academic year. Annual reports detailing water and power consumption in buildings are frequently provided. According to the literature review, a calendar year is the most often used timeframe in the publications examined. Data gaps within the designated reference period can be identified and accounted for as exceptions. Regardless of the chosen timescale, annual assessments require consistency in identifying the reference period. As the reference period varies throughout the year, breaking it up into smaller timeframes, such as specific semesters, is not recommended. Different available courses may require different amounts of equipment, and heating demands can fluctuate with changes in outdoor temperature [31]. Additionally, the year 2020 is the reference period for this O-LCA study.

1.6.3 Reporting flow

The reporting flow measures the productivity of HEIs and universities. An HEI primarily offers two services that constitute its academic output: instruction and scholarly research. The reporting flow describes Kabul University's academic activity for the 2020 reference year, which involved 889 academic staff, 325 administrative staff, and 23,452 students. Table 2 presents more detailed statistics for these indicators in the O-LCA of Kabul University.

Similar studies by Bueno et al. [11], Filimonau et al. [20], and Lukman et al. [37] addressed inconsistencies in how universities quantify and report their environmental performance. These authors harmonized the measurement of both organizational scale

Table 2 Chosen indicators for the O-LCA of Kabul University

Indicator	Amount	Unit	Reference Period
Number of Students	24,633	Person	Semester 2020
Number of Academic Staff	889	Person	2020
Number of Administrative Staff	325	Person	2020
Degree Programs	103	–	2021
Number of Graduates	3,677	Person	2020–2022
Funding	653,634,903	USD	2020
Area	23,320.3	m ²	2021
Number of Buildings	53	–	2022

indicators (building area, staff, and budget) and environmental performance indicators (energy use, emissions, and waste generation). Their work helped reduce data imbalances and improve comparability between institutional and operational assessments.

The indicators listed in Table 2 were selected in accordance with ISO/TS 14072 [30] and UNEP/SETAC [63] recommendations for defining an organization's system boundaries and relevant activity data in O-LCA studies. These indicators characterize the main operational and resource flows that determine the environmental performance of an HEI. They include academic activity indicators (number of students, graduates, and degree programs), human resource indicators (academic and administrative staff), and infrastructural indicators (annual budget and expenditure). This combination reflects the functional, physical, and economic dimensions of Kabul University that influence energy consumption, water use, waste generation, and transportation demands. Similar indicators have been successfully applied in previous O-LCA studies of universities and public institutions [11, 31, 36], ensuring methodological comparability and reproducibility.

1.6.4 System boundary

Establishing system boundaries for an HEI like Kabul University involves encompassing major functional areas such as teaching, research, and administration [31, 67]. In this study, gate-to-gate system boundaries were selected due to the absence of reliable downstream data on postgraduate outcomes (alumni environmental contributions and career impact), as well as upstream burdens such as embodied energy in construction and infrastructure. This approach allowed the study to focus on the most verifiable and direct operations at Kabul University, including building electricity and heating, generator-based fuel consumption, student and staff commuting, water usage, and solid waste generation. Reporting units should be established based on the outcomes of these activities, such as the number of students educated, research papers produced, or administrative services delivered [26]. The system boundaries of Kabul University as an HEI in Afghanistan are presented in Fig. 2.

A significant issue in defining the system boundary for Kabul University is the wide range of study programs, research initiatives, and corporate projects. After class, students participate in a wide range of activities that impact the environment, both directly and indirectly [31]. Many of these activities occur outside the scope of the university's operational control or lack measurable data. Therefore, a gate-to-gate approach was adopted to limit the assessment to core campus operations, specifically those related to teaching, learning, research, and administration offices activities. According to Jürgens et al. [31], Chatterton et al. [13] were the first to quantify the environmental impacts of research activities. Complete inputs and outputs associated with Kabul University's activities should be considered, and any activity exclusion must be justified. The facilities utilized during teaching, learning, and research activities should be included, as they contribute to the environmental impacts of HEIs.

In addition, upstream burdens related to construction materials, laboratory equipment, and embodied infrastructure energy were excluded due to the absence of localized Life Cycle Inventory (LCI) data for the Afghan context. Incorporating international proxy values was considered methodologically inappropriate due to differences in material sourcing, construction practices, and energy systems. Similarly, facilities such as the Afghanistan Information Center at Kabul University and other externally administered

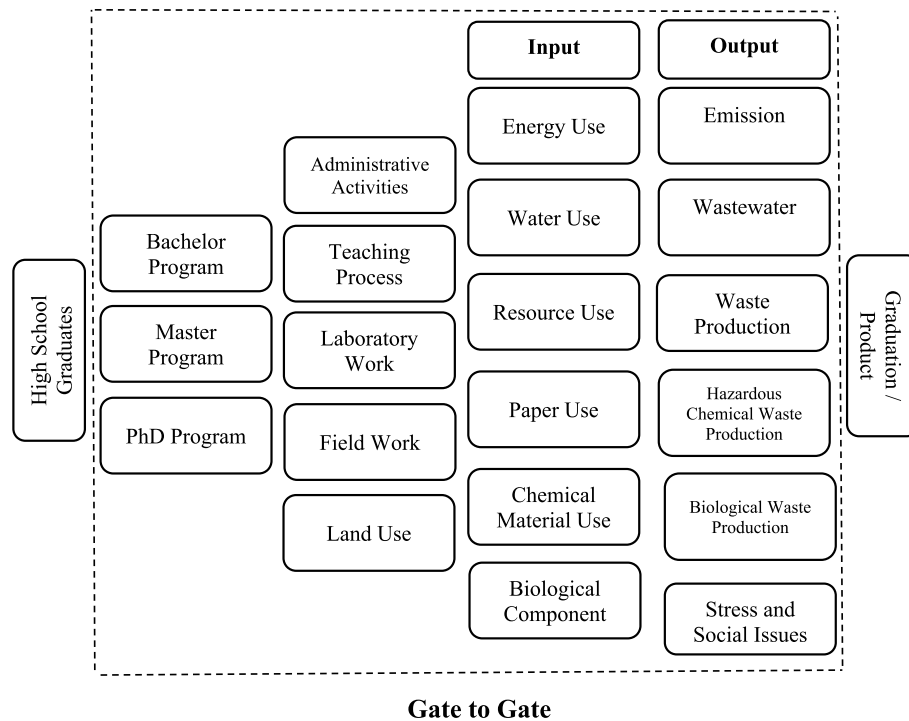


Fig. 2 System boundaries of the O-LCA study of Kabul University

organizations located within or near the campus were excluded from the analysis, as they fall outside the direct control of Kabul University's core administration. These inclusions and exclusions are visually summarized in Fig. 2, which illustrates the defined system boundary for this study and supports the justification for adopting the gate-to-gate model given the region's data and governance constraints.

The gate-to-gate approach used in this study excludes downstream impacts, such as the long-term environmental effects of graduates, the societal uptake of academic research, and collaborations with external stakeholders. These exclusions introduce truncation errors, as the full life cycle impacts of HEIs extend beyond campus operations. However, due to a lack of reliable data and methodological consensus for tracing such indirect impacts, especially in fragile and post-conflict settings like Afghanistan, this study prioritizes operational impacts with the highest data availability and institutional control. Future research should expand the system boundary to explore downstream effects as data systems and digital infrastructure improve.

1.6.5 Data collection and sources

The data collection process followed a structured approach to ensure the scientific rigor and reproducibility of this study. Both primary and secondary data were collected for the 2020 academic year as a reference year from multiple departments across Kabul University, each responsible for reporting within its operational scope. The Energy and Logistics Departments provided electricity and diesel fuel estimates for Kabul University based on generator logs and utility invoices. The Service Department of Kabul University contributed data on water and energy consumption and waste generation, while the Transport and Logistics Departments provided commuting estimates. The Academic Vice Chancellor's related department supplied data related to academic staff

and activities. The Vice Chancellor of Student Affairs' related departments provided information on students' campus occupancy and building usage schedules. Data were gathered through official written requests submitted to the responsible officers in each department.

Secondary data were collected from published literature and international reports, including the MoHE. Proxy data were supplemented using peer-reviewed studies of comparable universities [31, 36] to fill information gaps caused by data scarcity, which is typical in post-conflict contexts.

Due to incomplete or inconsistent logs in several units, missing values were addressed using various strategies, such as monthly or seasonal extrapolation based on partial-year records and expert estimates verified through cross-checks with administrative staff. When internal data were unavailable, proxy data were employed, considering Afghanistan's relevant regulations and bylaws in the finance and transport departments. For example, waste generation per capita in Kabul University was estimated using published studies from similar regional settings [36], calibrated with Kabul University's known student population and service model.

1.6.6 Life cycle inventory analysis

1.6.6.1 Life cycle inventory The LCI of Kabul University was developed using systematically collected primary and secondary data described in Sect. 2.2.5 (Data Collection and Sources). The LCI data were compiled from a combination of data collection checklists, official departmental records, and on-site verification conducted at Kabul University. Additionally, a checklist was shared with the relevant department to ensure the systematic retrieval and validation of the required evidence. To ensure data reliability, each indicator was measured or estimated in triplicate whenever possible, using departmental logs, observations, and checklist confirmations. The results were triangulated with other related departments and the archive department at Kabul University and the MoHE to minimize potential inconsistencies. This triangulated and multi-source approach ensured that the LCI data were consistent, transparent, and reproducible despite the data limitations typical of Afghan HEIs. The key inventory categories are presented in Table 3.

To address data gaps common in underdeveloped nations such as Afghanistan, approaches such as using proxy data and literature-based estimates were used when direct measurements were unavailable. In cases where direct energy consumption data were not accessible, estimations were derived from comparable universities in Germany [31] and adjusted to account for variations in scale and infrastructure [47]. Sensitivity analyses were then conducted to assess the impact of data uncertainty on the study results by generating multiple scenarios with varied data inputs [25]. By employing these methods, a more robust O-LCA model was developed, capable of producing reliable outcomes despite limited data availability in the Afghan higher education context.

Table 3 Categories of potential inventories for HEIs

Category	Inventory Flows
Energy supply	Electricity, heat consumption, and fuels
Infrastructure	Office furnishings and IT equipment
Operating materials	Water consumption and office supplies
Transport	Commuting of employees and students
Waste	Waste

1.6.6.2 Life cycle impact assessment To assess the environmental impacts of HEIs and universities, it is crucial to use a suitable LCIA technique. The life cycle impact assessment (LCIA) approach should offer extensive geographical coverage [60]. Additionally, it is important to include as many impact categories as possible, particularly considering the significant disparity between the number of carbon footprint studies and LCA investigations. Several LCIA methods are available for conducting LCA research. The International Standard for Life Cycle Assessment (ISO 14040–14044) does not prescribe a specific LCIA method, resulting in different LCIA methods adopted from one study to another [18, 34].

The ReCiPe 2016 approach seems to be the most suitable LCIA method for conducting an LCA of HEIs and universities. The approach was chosen not only for its robust categorization but also because it offers greater flexibility in data-limited contexts. Its compatibility with missing regional impact factors and ease of scenario modeling is crucial in assessing Kabul University's environmental impacts using incomplete datasets. The dataset incorporates normalization variables for Europe and provides a comprehensive global perspective, encompassing all prevalent effect categories. Simultaneously, it is the methodology endorsed by the European Commission in the Organization Environmental Footprint [50], which is based on ISO/TS 14072. The coverage extends to the impact categories of acidification, ionizing radiation, human toxicity (both carcinogenic and non-carcinogenic), ozone depletion, eutrophication of the Earth's atmosphere, freshwater and terrestrial ecosystems, ecotoxicity of freshwater, land and water utilization, resource depletion for fossil fuels, and resource utilization for metals and minerals, all of which are factors contributing to climate change and ozone depletion [31, 49].

1.6.6.3 Life cycle interpretation Life cycle interpretation is the final stage of LCA when conclusions and suggestions are derived from the results of the LCI and LCIA. When conducting an O-LCA of infrastructure, it is essential to thoroughly analyze and effectively convey many significant sources of uncertainty [33, 59].

The LCI of Kabul University, as an organization within the higher education sector, was prepared based on the primary data possibly included in the system boundary. Data availability is a significant challenge in data collection and accuracy. The data were collected from the offices of the Chancellor, Vice Chancellor of Academic Affairs, Vice Chancellor of Administration and Finance Affairs, and Vice Chancellor of Student Affairs. Moreover, financial data were also obtained from the MoHE, Afghanistan, which were shared with the Ministry of Finance, Afghanistan, for further processing and control.

In this study, a structured sensitivity analysis was conducted to assess how uncertainty in input data affects the O-LCA results for Kabul University. The parameters tested included electricity consumption, diesel fuel use, water consumption, and solid waste generation, as these represent the most influential contributors to environmental impacts in the inventory phases. Each parameter was systematically varied by $\pm 10\%$, $\pm 20\%$, and $\pm 30\%$ around its baseline value to represent realistic fluctuations in operational records and measurement uncertainties. The variation range was determined based on institutional data quality, expert judgement, and benchmarks from previous O-LCA studies [14, 25, 31, 36]. Using SimaPro 8.0 (Ph.D. version), each scenario was calculated under the ReCiPe 2016 Midpoint (H) method, and the results were

compared across major impact categories such as Global Warming Potential (GWP) and Fossil Resource Depletion (FRD). Variations in electricity and diesel fuel consumption caused the highest deviation up to $\pm 15\%$ GWP. This structured approach enhances methodological transparency, reproducibility, and interpretive reliability of the O-LCA outcomes for Kabul University, consistent with international guidance on uncertainty and sensitivity analysis in LCA.

1.6.6.4 Data quality The data were collected from relevant departments at Kabul University and double-checked with other related departments. For example, the quantity of fuel was mentioned in the Logistics Department of Kabul University and also found in the Finance Department. Additionally, some data reported by related departments but not found in others were rechecked with the department's archive.

To effectively communicate the reliability of the outcomes, it is essential to incorporate a framework for evaluating data quality. This framework can assess data based on several criteria, such as completeness, consistency, and accuracy. By evaluation of the data quality in the O-LCA, stakeholders can gain a clearer understanding of the strength and reliability of the findings, as well as identify target areas that can be improved [26].

This study incorporated a built-in sensitivity analysis to evaluate the robustness of findings under conditions of uncertain or missing data, especially regarding fuel use and transportation routes. These uncertainties were addressed through Monte Carlo simulation and impact range estimation, acknowledging that data inconsistencies are an unavoidable feature of the Afghan HEI context.

To improve transparency and traceability, a simplified data quality assessment matrix was applied. Data were evaluated across five dimensions: temporal coverage, geographical representativeness, technical relevance, completeness, and precision, as shown in Table 4, using a scale from 1 (high quality) to 5 (low quality). Primary data from university departments, such as electricity and fuel consumption, scored 1–2 in most categories. In contrast, estimated or proxy data, such as commuting distances and waste generation, scored 3–4 due to lower precision and completeness. The matrix helped highlight limitations while justifying the use of proxy sources in the absence of digital or historical datasets.

2 Results and discussion

2.1 Assessment of the organizational life cycle assessment to evaluate the environmental impacts of Kabul University

This study presents the first application of O-LCA in the context of post-conflict HEIs in Afghanistan. The analysis focuses on the outcomes of the reporting organization in 2020 and includes a thorough investigation of several scenarios evaluated in this study. The results discuss the environmental performance of Kabul University during 2020,

Table 4 Data quality scoring matrix for Kabul University's O-LCA input

Data Category	Temporal	Geographic	Technological	Completeness	Precision
Electricity	1	2	1	2	1
Generator Fuel	1	1	1	2	2
Commuting	3	2	3	3	3
Water Consumption	1	1	1	2	2
Waste Generation	3	2	2	3	3

providing insights into the impact categories most affected by academic activities. Unlike O-LCA studies conducted in developed countries, this assessment addresses critical infrastructural and data limitations, revealing both environmental burdens and systemic challenges unique to fragile institutional settings. The findings aim to support context-sensitive sustainability strategies for HEIs facing similar problems.

The life cycle impact assessment was conducted using the ReCiPe 2016 methodology. The comprehensive environmental impacts resulting from the teaching and learning activities of Kabul University throughout the specified timeframe are presented in Table 5. The LCIA phase aims to examine the potential adverse impacts using the LCI findings. The inventory data were processed using SimaPro version 8.0 (Ph.D. version). The impacts were calculated based on the activities of Kabul University using the ReCiPe 2016 method. The Ecoinvent 3's allocation cut-off by the classification library was utilized for data processing. This methodology employs the damage-oriented approach, also known as the end-point approach, for conducting impact assessments. The end-point environmental LCIA method transforms impact indicators into three damage categories that are more comprehensible and can be conveniently interpreted. The cumulative environmental impacts resulting from Kabul University's educational activities during the specified timeframe are presented in Table 5. The impact categories included in this study were also examined by Bueno et al. [11], Furlanet and Tiago [22], and Jürgens et al. [31].

Table 5 presents the environmental impacts of Kabul University's academic activities in 2021, which are organized based on the ReCiPe 2016 impact assessment method. The results are categorized into three damage categories: human health, ecosystem, and resources. The main impact on human health arises from the formation of fine

Table 5 The total environmental impacts of the academic activities of Kabul University in 2020 based on the ReCiPe 2016 impact assessment method and classification based on damage categories

Impact Category	Sub-Category	Unit	Results of Life Cycle Assessment
Human Health	Stratospheric ozone depletion	DALY	0.00155134
	Ionizing radiation	DALY	0.00471964
	Ozone formation, human health	DALY	0.01438193
	Water consumption, human health	DALY	0.14768179
	Human carcinogenic toxicity	DALY	0.26969363
	Human non-carcinogenic toxicity	DALY	0.42604136
	Global warming, human health	DALY	8.56378089
	Fine particulate matter formation	DALY	16.2356596
Ecosystem	Water consumption, aquatic ecosystems	species.yr	4.6007E-08
	Marine eutrophication	species.yr	8.0365E-08
	Global warming, freshwater ecosystems	species.yr	7.0594E-07
	Marine ecotoxicity	species.yr	1.7016E-06
	Freshwater ecotoxicity	species.yr	2.8811E-06
	Terrestrial ecotoxicity	species.yr	0.00015637
	Land use	species.yr	0.0008575
	Water consumption, terrestrial ecosystems	species.yr	0.00154018
	Freshwater eutrophication	species.yr	0.00119716
	Ozone formation, terrestrial ecosystems	species.yr	0.00205289
	Terrestrial acidification	species.yr	0.00966604
	Global warming, terrestrial ecosystems	species.yr	0.02584017
Resources	Mineral resource scarcity	USD2013	3,882.65201
	Fossil resource scarcity	USD2013	294,349.291

particulate matter, which is quantified by a disability-adjusted life year (DALY) value of 16.2356596. This impact is most likely a result of the emissions produced by the university's energy consumption, transportation, and other activities related to its operations. The impact of global warming on human health is significant, with a value of 8.56378089. The overall burden of disease was assessed through the utilization of DALY.

Marine eutrophication has a significant impact on the ecosystem, with a value of $8.0365\text{E-}08$ species.yr. Other than that, ecosystem degradation is also caused by global warming, freshwater ecosystems ($7.0594\text{E-}06$ species.yr); water consumption, aquatic ecosystems ($4.6007\text{E-}08$ species.yr); freshwater ecotoxicity ($2.8811\text{E-}06$ species.yr); and marine ecotoxicity ($1.7016\text{E-}06$ species.yr). Meanwhile, the impacts of terrestrial ecotoxicity; land use; water consumption, terrestrial ecosystems; freshwater eutrophication; ozone formation, terrestrial ecosystems; terrestrial acidification; and global warming, terrestrial ecosystems, resulting from the academic activities of Kabul University, are relatively smaller.

Table 5 shows that among the damage categories evaluated in the O-LCA, impacts on human health, particularly from fine particulate matter formation and global warming, were the most significant contributors to Kabul University's environmental footprint. In comparison, ecosystem-related impacts such as acidification and terrestrial ecotoxicity were relatively less pronounced. This result highlights how the university's infrastructure on fossil fuel-based electricity generation, insufficient transport, and limited waste infrastructure directly endangers human health. These trends are consistent with other HEIs in low-resource or post-conflict settings, where constrained infrastructure leads to elevated exposure risks for surrounding populations [36]. This underscores the need for institutional strategies aimed at adopting cleaner energy, reducing emissions, and improving air quality.

Figure 3 presents the percentage contributions of various subcategories to the human health impact category, based on the environmental assessment data. Fine particulate

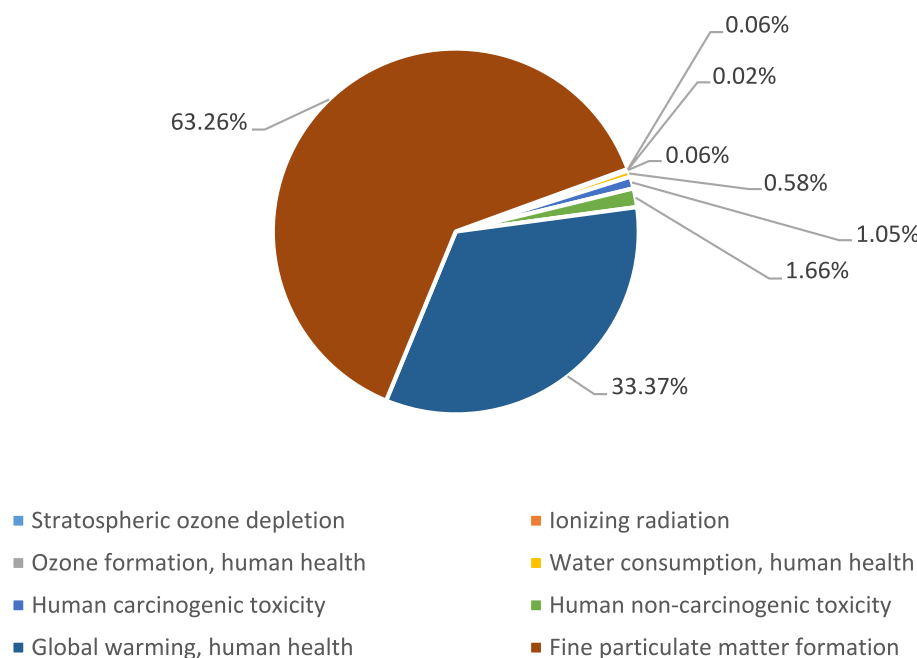


Fig. 3 Percentage distribution of human health subcategories

matter formation is the primary contributor, accounting for 63.26% of the total impact. This finding aligns with research highlighting the detrimental health effects of particulate matter exposure, such as respiratory and cardiovascular disorders [52]. The second-largest contributor is global warming, with human health accounting for 33.37%, indicating health concerns related to climate change, including heat-related illnesses and vector-borne infections [23]. Other subcategories, including human non-carcinogenic toxicity (1.66%) and human carcinogenic toxicity (1.05%), underscore the effects of chemical exposure on human health, corroborating results from toxicological research [32]. Minor contributors include water consumption, human health (0.575%); ozone formation, human health (0.056%); ionizing radiation (0.018%); and stratospheric ozone depletion (0.06%), signifying relatively negligible impacts on overall human health. These findings highlight the need for specific strategies aimed at reducing air pollution and mitigating the impacts of climate change to improve public health outcomes.

Comparing these results offers important context for other academic O-LCA studies. For example, Lo-Iacono-Ferreira et al. [36] discovered that energy use accounted for 70–80% of all environmental impacts in Spanish colleges, making it the main contributor to those impacts. In contrast, the current analysis reveals a more balanced distribution of impacts among building operations (19.5%), transportation (24.7%), and energy (55.8%). This discrepancy can be attributed to the particular difficulties faced by Kabul University, such as its inadequate public transit system and reliance on diesel generators for energy.

Figure 4 depicts the percentage contributions of several subcategories to the ecosystem effect category, emphasizing that global warming, terrestrial ecosystems (62.54%), is the predominant contributor. This finding aligns with Rustad et al. [55], who highlighted the complex and diverse reactions of terrestrial ecosystems to global warming, encompassing changes in biodiversity and ecosystem services. Other significant contributors include terrestrial acidification (23.40%) and ozone formation, terrestrial ecosystems (4.97%), consistent with research linking air pollution and acid deposition to soil degradation and biodiversity loss [3]. Minor contributors such as freshwater eutrophication (2.90%) and terrestrial ecotoxicity (0.38%) suggest limited effects from agricultural runoff

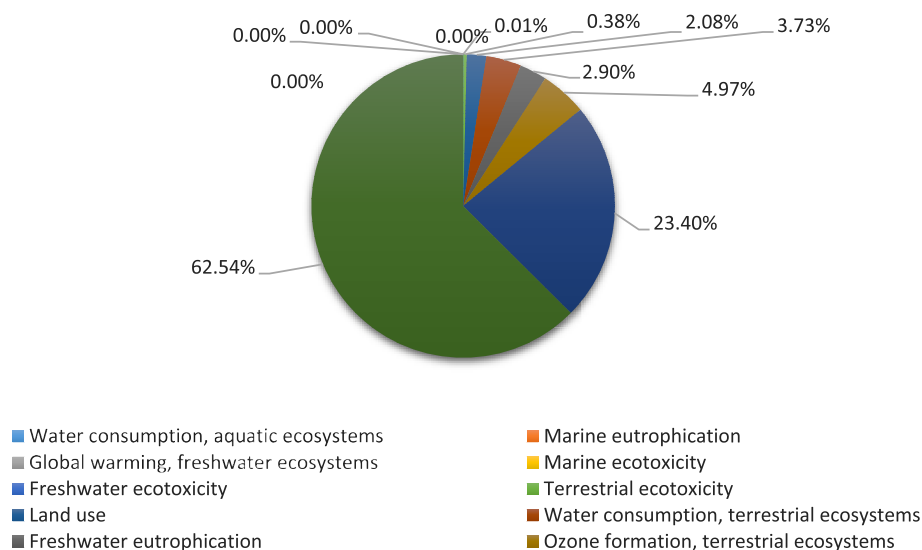


Fig. 4 Percentage distribution of ecosystem subcategories

and chemical contamination, as noted by Strokhal et al. [62]. The insignificant contributions of categories like marine eutrophication (<0.01%) highlight the limited extent of marine impacts within this evaluation framework. These results indicate that addressing climate change and reducing air pollution are essential for mitigating ecosystem damage.

The depletion of fossil fuels is the most notable consequence in the fuel category, amounting to a cost of 294,349.291 USD₂₀₁₃. This impact is probably a result of the university's reliance on fossil fuels for transportation and energy. There is also a concern about the scarcity of mineral resources, which amounted to 3,882.65201 USD₂₀₁₃. A similar finding was reported by Jürgens et al. [31] in the study of O-LCA of a university as an HEI.

Figure 5 illustrates the extent to which various operational areas at Kabul University contribute to specific impact categories. The primary factors that contribute significantly are electricity, transportation activity, and building operations (hostels). Electricity accounts for the majority of the impact across all 22 categories.

Consequently, the LCA results emphasize how crucial it is for Kabul University to address its environmental effects, particularly in the domains of air pollution, GHG emissions, and resource depletion. Adopting sustainable practices, such as implementing energy-efficient measures, utilizing renewable energy sources, and implementing waste reduction strategies, could help mitigate these impacts. Furthermore, the impact characterization demonstrates the proportional contribution of each impact category. However, direct comparisons between categories are not possible, as the data represent the relative distribution within each category rather than the actual amount.

Based on Fig. 5 and the data presented in Table 5, the impacts of the O-LCA on Kabul University were analyzed. According to the contribution to global warming, the university's operations have a substantial impact on global warming in five areas: water consumption, aquatic ecosystems, marine eutrophication, global warming, and freshwater ecosystems. The primary factors responsible for these impacts are electricity, transportation, specifically passenger coaches, and building operations, particularly hostels.

Fine particulate matter, global warming, and human health, which have negative impacts, are mostly attributed to electricity and transport operations. This underscores

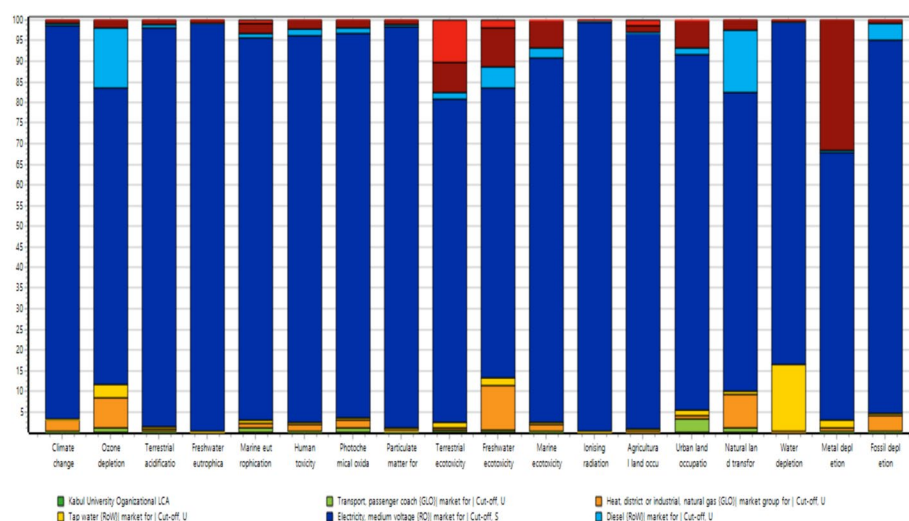


Fig. 5 Contribution of environmental impact categories

the necessity for implementing renewable energy sources and sustainable transportation options within the university.

The formation of fine particulate matter (0.033826655 DALY) and the impact of ozone formation on human health (0.000196331 DALY) and terrestrial ecosystems (2.82039E-05 species.yr) are major issues. According to Abbass et al. [2], these effects are primarily caused by transportation and construction activities. University operations have a measurable impact on human carcinogenic toxicity (0.26969363 DALY), human non-carcinogenic toxicity (0.42604136 DALY), and different ecotoxicity impacts. The harmful impacts mainly result from electricity usage and transportation [71].

The impacts of fossil resource scarcity (valued at 294,349.291 USD2013) and mineral resource scarcity (valued at 3,882.65201 USD2013) are significant, which are primarily driven by transportation, electricity usage, and building operations. This highlights the significance of shifting toward renewable energy sources and advocating for resource efficiency [24]. Finally, the O-LCA results of Kabul University emphasize the need for Kabul University to prioritize sustainable practices in areas including transportation, energy consumption, and resource management to mitigate its environmental impacts.

Beyond the quantitative results, the findings reflect broader challenges faced by Kabul University in a post-conflict context. The heavy reliance on generator fuel, limited waste management, and absence of a data system are not only environmental burdens, but also structural indicators of institutional fragility. These limitations underscore the urgent need for investment in green infrastructure, capacity building, and digital monitoring tools.

Furthermore, this study identifies important research gaps, including the need to assess downstream academic impacts, trace material flows across research laboratories, and quantify student lifestyle emissions in dormitory settings. Future research should build upon this baseline O-LCA to incorporate broader social and circular economy perspectives.

The findings also have policy implications. The MoHE and the National Environmental Protection Authority in Afghanistan, along with international donors, can utilize these results to develop sustainability benchmarks for universities. Implementing national-level LCA reporting standards, incentivizing solar power integration, and supporting green procurement in HIEs are practical strategies to reduce the sector's environmental footprint. Furthermore, the methodological framework in this study can be adopted by other post-conflict or resource-constrained institutions aiming for climate-resilient development.

Based on the overall evaluation, the organization excels in numerous subcategories, particularly those related to water usage, toxicity, and various environmental impacts. However, there are notable areas that require improvement, such as the formation of fine particulate matter and the effect of global warming on human health, terrestrial ecosystems, and freshwater ecosystems. Terrestrial acidification refers to the process of increasing acidity in land ecosystems.

These results can be contextualized by comparison with other O-LCA studies, as shown in Table 6. For example, Jürgens et al. [31] found electricity to be the dominant contributor, accounting for 60% of impacts at a German university. Similarly, Lo-Iacono-Ferreira et al. [36] reported that energy-related impacts contributed up to 80% in Spanish universities. However, in the current study, although electricity is dominant,

Table 6 Comparative summary of key environmental impact contributions in O-LCA studies of HEIs

Study	Country/Context	Main Environmental Contributor	Transport Share	Resource Use
Jürgens et al. [31]	Germany (developed)	Electricity (60%+)	15%	Fossil fuels and heat
Lo-Iacono-Ferreira et al. [36]	Spain (developed)	Energy (70–80%)	Low (not dominant)	Mostly electricity
Bueno et al. [10]	Spain (developed)	Energy use and infrastructure	Low	Balanced across sectors
Pelletier et al. [49]	USA (developed)	Energy (buildings)	~ 10–20%	Moderate water and waste

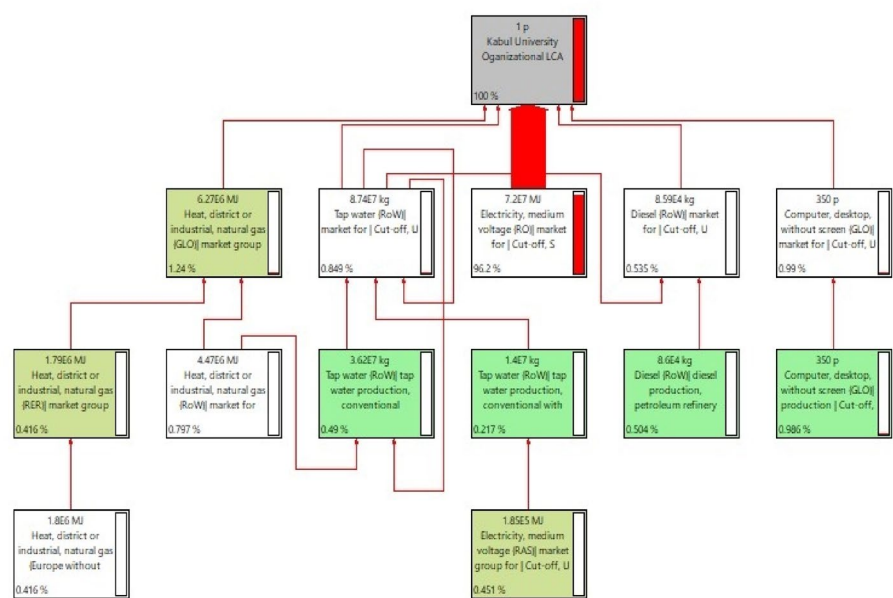


Fig. 6 The tree diagram of Kabul University indicating organizational impacts generated using SimaPro software

transportation (24.7%) and building operations (19.5%) are also major contributors. This broader distribution reflects the post-conflict infrastructural disorganization detailed at Kabul University.

It is essential to acknowledge the limitations of the data quality and the potential uncertainties in the O-LCA findings. To address this, the method described by Heijungs & Huijbregts [25] was used, and a Monte Carlo simulation was performed to evaluate the reliability of the results. The simulation revealed a moderate degree of uncertainty in the confidence ranges for the two primary impact categories (the formation of fine particulate matter and global warming, with uncertainties of $\pm 15\%$ and $\pm 12\%$, respectively). The main source of these uncertainties is the lack of data in the estimates and records of energy consumption related to transportation.

Using the data from the O-LCA results presented in Fig. 6, the environmental impacts of Kabul University's activities can be analyzed as follows. The tree diagram clearly shows that energy consumption is the primary contributor to the university's environmental impact, accounting for 55.8% of the overall impact. Transportation accounts for 24.7% of the total impact, while building operations, particularly hostels, contribute 19.5%. The sum of these three categories accounts for the entire 100% of the evaluated impact.

The significant proportion of electricity consumption (55.8%) highlights the university's primary concern regarding energy usage. This finding aligns with other research on the environmental impacts of universities, such as the study by Jürgens et al. [31], which also identified electricity as a major factor in their LCA of an HEI.

The contribution by the transportation sector of 24.7% indicates a substantial impact resulting from commuting and other transportation-related activities. These findings align with the research conducted by Abbass et al. [1], which revealed that transportation has a significant role in environmental degradation in university environments, particularly concerning air pollution and GHG emissions.

Building operations, particularly the inclusion of dormitories, account for 19.5% of the overall contribution, underscoring the importance of integrating residential facilities into sustainability initiatives at universities. This component is often overlooked in conventional LCA studies, but it is effectively addressed in this approach, known as O-LCA.

The comprehensive assessment is facilitated by the tree diagram, which provides a clear representation of the varying degrees of influence that different university operations have on its total environmental impact. The comprehensive nature of O-LCA is emphasized as a significant advantage in evaluating environmental impact assessments in HEIs [22].

2.2 Comparative analysis and uncertainty assessment

Compared to the study by Lo-Iacono-Ferreira et al. [36] on Spanish universities, Kabul University's environmental impact related to energy consumption is approximately 25% higher. This difference may be attributed to the university's reliance on diesel generators and less energy-efficient infrastructure. In contrast to the 70–80% energy impact observed in Spanish institutions, the analysis of Kabul University shows a balanced distribution of impacts across building operations (19.5%), transportation (24.7%), and energy (55.8%). This difference most likely reflects the unique challenges faced by Kabul University, notably its reliance on diesel generators and poor public transportation. Abbass et al. [1] found that transportation plays a significant role in the environmental impacts of universities, especially in developing countries with inefficient public transit systems.

A study by Jürgens et al. [31] at a German university discovered that transportation accounted for only 15% of the total environmental impacts, which is lower than the 24.7% reported for Kabul University. This difference highlights the need for improved environmentally friendly transportation solutions in the Afghan context. For uncertainty analysis, using the method described by Heijungs & Huijbregts [25], two main impact categories of fine particulate matter formation and global warming impacts in the simulation resulted in the confidence ranges of $\pm 15\%$ and $\pm 12\%$, respectively. These moderate levels of uncertainty are primarily due to gaps in transportation-related energy consumption data.

These findings directly address the central research objective of this study: to assess the environmental impacts of higher education services at Kabul University using the O-LCA framework. By identifying the most significant environmental hotspots, such as fine particulate matter formation, fossil fuel dependence, and transportation-related emissions, the results provide a comprehensive picture of the environmental burdens embedded in institutional activities. This validates the significance of O-LCA as a

decision-support tool in post-conflict academic contexts and highlights its potential for guiding targeted sustainability interventions in low-resource university contexts.

Additionally, the results empirically validate the viability of applying ISO 14072-based O-LCA in environments with constrained data systems, aligning with previous work by Lo-Iacono-Ferreira et al. [36] and Jürgens et al. [31]. By doing so, the study not only achieves its stated objective but also contributes to expanding the operational boundaries of environmental assessment in fragile higher education systems.

2.3 Theoretical implications

This study advances the theoretical understanding of O-LCA within HEIs, especially in post-conflict contexts. While previous O-LCA studies in higher education have mainly focused on well-resourced institutions with comprehensive datasets [11, 31], our findings reveal significant theoretical gaps in the current literature. Firstly, there is a lack of operationalized frameworks suitable for data-poor institutions in fragile or post-conflict contexts, where digital infrastructure and consistent records are limited [36]. Second, the definition of system boundaries remains inconsistent across studies, with few addressing the challenges of including or excluding externally-managed facilities or research activities [26]. Third, dormitory-based emissions and student lifestyle impacts, predominantly in institutions with on-campus housing, are rarely modeled, despite their notable contribution to environmental loads. By addressing these issues, our study contributes to refining the O-LCA methodology to better fit understated institutional settings, paving the way for future research on methodological adaptability and equity in environmental assessment.

Our findings support the concept of "sustainability under constraints," indicating that organizations operating in resource-constrained settings must address complex sustainability concerns [16]. The heavy reliance on fossil fuel-derived energy and the significant impact of transportation underscore the necessity to incorporate resilience thinking into sustainable frameworks for HEIs facing vulnerability [36]. Furthermore, this study contributes to the current literature by demonstrating that O-LCA is an effective tool for evaluating environmental impacts at universities, offering a comprehensive perspective that encompasses both direct and indirect effects. This aligns with recent studies highlighting the significance of O-LCA in identifying environmental hotspots and guiding sustainability measures in educational institutions [42].

The conclusions of this study hold significant practical implications for Kabul University and similar organizations pursuing sustainability:

1. **Energy Transition:** The institution should prioritize the shift to sustainable energy sources, particularly solar electricity, which is abundant in Afghanistan. Implementing solar energy systems could reduce the environmental impact of energy use by up to 40%, based on similar projects in other developing countries [38].
2. **Sustainable Transportation:** Developing a comprehensive sustainable transportation strategy, including carpooling initiatives and improved public transport connections, could significantly reduce the 24.7% impact attributed to transportation. Universities that have implemented similar initiatives have experienced a decrease in transport-related emissions by 15–25% [53].
3. **Green Building Practices:** Emphasizing sustainable building techniques for new constructions and renovations, especially in student housing, could reduce the 19.5%

impact from building operations. Energy-efficient architecture may potentially reduce this impact by 30–50% [54].

4. Curriculum Integration: Integrating these environmental impact results into the curriculum across multiple disciplines could enhance student knowledge and encourage grassroots sustainability initiatives [45].

By adopting these strategies, Kabul University could significantly reduce its environmental impact while exemplifying sustainable practices in higher education in Afghanistan and other post-conflict areas.

3 Conclusions

This study applied an O-LCA to evaluate the environmental performance of Kabul University. The results revealed considerable environmental impacts across multiple categories, particularly those related to human health and global warming potential. Electricity consumption, transportation, and building operations were identified as significant contributors to these impacts. The primary environmental impacts included the formation of fine particulate matter (16.24 DALY) and the impact of global warming on human health (8.56 DALY). It is recommended that Kabul University implement energy efficiency measures, develop sustainable transportation options, modernize building systems, integrate green building concepts, and establish an EMS to address these challenges. Adopting sustainable practices in these areas will not only reduce environmental damage but also offer opportunities for long-term economic savings, especially in energy and resource utilization. Furthermore, the adoption of sustainability initiatives informed by these findings can reinforce Kabul University's position as a pioneer in environmental stewardship within Afghan HEIs. Consequently, the O-LCA results for Kabul University are applicable to other HEIs in post-conflict environments, emphasizing shared environmental constraints and opportunities for improvement. These initiatives align with several UN SDGs, specifically SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). Kabul University can enhance its environmental performance and exemplify sustainable practices in higher education in Afghanistan and other post-conflict areas.

This work advances the theoretical knowledge of O-LCA applications in higher education, especially in post-conflict contexts. By demonstrating how O-LCA can be adapted for resource-constrained environments, it expands existing frameworks and provides a model for evaluating environmental impacts in challenging settings. The findings have direct implications for Kabul University and similar institutions. Implementing energy-efficient technologies could reduce damage caused by electricity up to 30%. Additionally, transportation-related emissions could be reduced by 15–25% through the development of a sustainable transportation plan that includes carpooling and improved public transportation connections. The 19.5% impact from building operations could be mitigated by employing green building techniques in new construction and renovations. However, it is critical to acknowledge the study's limitations. In the Afghan context, data quality and availability posed challenges, requiring certain assumptions and estimations.

Despite the comprehensive scope of this O-LCA study conducted at Kabul University, several limitations must be acknowledged to contextualize the findings and qualify their generalizability. The gate-to-gate system boundary excluded downstream and long-term impacts, such as the environmental effects of graduates' future activities and the

dissemination of research outcomes. The exclusion of these factors introduces potential truncation errors, which may underestimate the university's total organizational footprint. Due to limited data availability, certain parameters, such as commuting distances and waste composition, were estimated using proxy values and assumptions, thereby reducing precision. Additionally, variations in behavioral patterns among students living in dormitories, such as energy and water use, were not disaggregated in the examination, which could affect intra-campus comparisons. The assessment focused exclusively on environmental indicators and did not include the social or economic dimensions of sustainability, which are also crucial in higher education settings. The university's heavy reliance on diesel generators also introduces uncertainty, as local variations in fuel quality and combustion efficiency influence emission estimates. Moreover, the study reflects a post-conflict institutional setting; therefore, the findings may not be directly generalizable to universities in more developed countries. These limitations highlight the need for future research to apply longitudinal designs, integrate multi-criteria sustainability frameworks, and conduct regional comparisons across HEIs operating under fragile conditions. These approaches would be able to capture dynamic institutional variations over time, improve the robustness of sustainability assessments, and update more context-sensitive environmental strategies.

Unusual occurrences or long-term trends may not be captured within the one-year timeframe of 2020. Furthermore, university activities during the study period could have been affected by the COVID-19 pandemic, which could have affected the data's representativeness. Moreover, longitudinal studies should be the main focus of future research to document changes in environmental impacts and the effectiveness of interventions over time. Comparative studies conducted in several post-conflict countries could provide insights into the environmental elements influencing university sustainability. Furthermore, exploring how social and economic factors can be integrated into environmental assessments may offer a more comprehensive evaluation of sustainability in universities operating in challenging environments. The findings of this research also have important policy implications. They highlight the necessity of focused finance and capacity-building initiatives to support environmental projects at post-conflict HEIs. Policymakers should consider offering incentives for the adoption of renewable energy, environmentally friendly architectural techniques, and sustainable transportation infrastructure in academic institutions. Moreover, incorporating sustainability criteria into higher education accrediting processes could promote systemic improvements.

Acknowledgements

The authors would like to thank Kabul University for providing data from different directorates and departments.

Author contributions

Wafaurahman Wafa: Writing original draft, data analysis, and conceptualization; Amir Hamzah Sharaai: Conceptualization, method, review & editing, and supervision; Nitanan Koshy a/IMathew: Review & editing, and supervision; Noor Ahmad Akhundzada: Review & editing, and supervision.

Funding

The authors declare that there are no funding affiliations with any individuals or groups that could improperly affect or influence the findings presented in this study.

Data availability

The data supporting the findings of this research will be available from the corresponding author upon reasonable request.

Declarations

Ethical approval and consent to participate

The authors declare that this study does not involve live vertebrates, higher invertebrates, or human subjects, ethical approval and informed consent statement are not applicable.

Competing interests

The authors declare no competing interests.

Received: 28 August 2025 / Accepted: 26 December 2025

Published online: 09 March 2026

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