International Journal of Environmental Science and Technology (2026) 23:356
https://doi.org/10.1007/s13762-026-07152-x

ORIGINAL PAPER

Achieving over 45% greenhouse gas reduction in a large University Amphitheatre: a life cycle assessment in Cameroon

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Received: 29 September 2025 / Revised: 20 January 2026 / Accepted: 25 February 2026

Abstract

Life Cycle Assessment (LCA) offers a comprehensive and rigorous framework for evaluating the environmental performance of buildings across all stages of their life cycle. This study assesses the full life cycle impacts (construction, operation, renovation, and demolition) of Amphitheatre 1001 at the University of Yaoundé I and evaluates the effectiveness of several mitigation strategies. Using the PLEIADES software suite, which integrates dynamic thermal simulation and LCA modelling, five scenarios were analysed: mobility management, photovoltaic (PV) solar energy production, a combined mobility-PV scenario, rainwater harvesting, and building orientation. Results reveal that the combined mobility and PV scenario delivers the largest environmental benefit, achieving a 45.57% reduction in greenhouse gas emissions and an average cumulative reduction of 26.42% across all impact categories over an 80-year life cycle. The PV-only scenario yields an average reduction of 18.07%, while mobility management alone achieves 8.35%. Rainwater harvesting produces a marginal improvement (0.23%), and orientation changes have no measurable influence on environmental performance. These findings highlight the critical role of integrated energy and mobility strategies for achieving significant environmental gains in high-occupancy educational buildings located in tropical regions.

Editorial responsibility: Samareh Mirkia.

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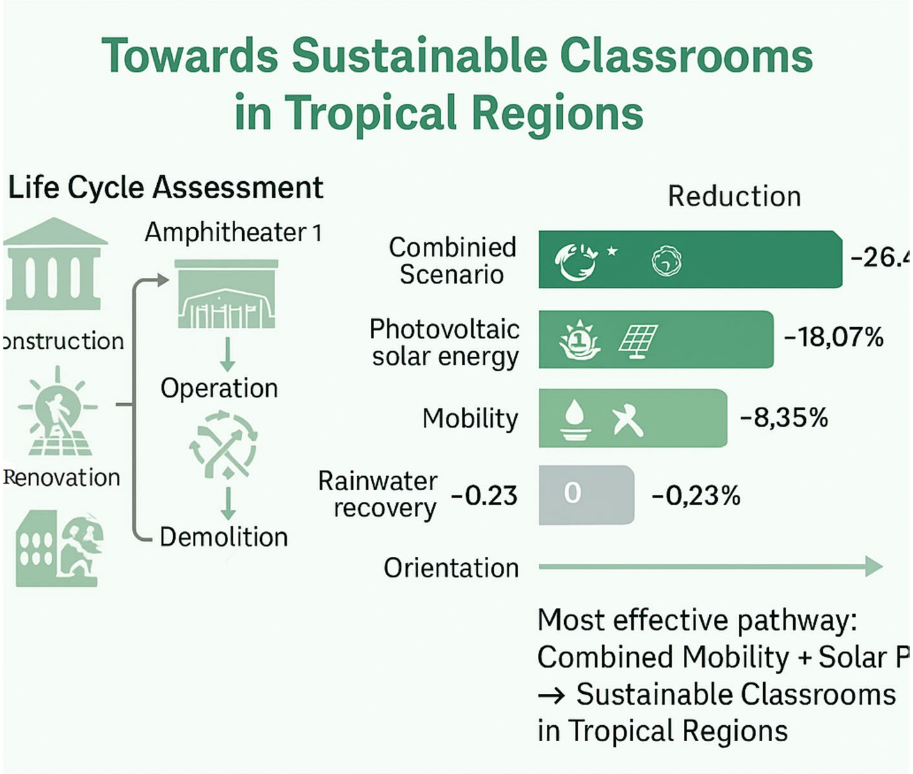
Graphical abstract



CA-based scenario analysis demonstrates that combining solar energy and obility management achieves the highest environmental benefits (26,42 % red

Keywords Commercial building · Environmental impact · Tropical region · Life cycle assessment

Introduction

The growing awareness of environmental issues and the need to preserve natural resources has led to increased attention to the impact of infrastructure on the environment. Climate change is now affecting the entire world. Extreme weather conditions, such as droughts, heatwaves, heavy rainfall, floods, landslides, rising sea levels, ocean acidification, and biodiversity loss, are becoming increasingly frequent worldwide. Limiting global warming to below 1.5 °C by 2050 is essential for the future of humanity (Mohammed et al. 2013).

The construction sector is one of the largest consumers of natural resources, particularly fossil fuels. It is responsible for more than a third of global greenhouse gas emissions, resulting in significant environmental impacts. In industrialized countries, this sector accounts for 42% of energy consumption (Mohammed et al. 2013), 35% of greenhouse gas emissions (Adel et al. 2021), and 50% of material extractions (Osman et al. 2023). Due to population growth, energy demand is expected to rise by 53% over the next decade, leading to a significant increase in emissions concentration. Globally, emissions from the construction sector come from the energy used for heating, cooling, lighting, ventilation, hot water supply, and air conditioning (Rock et al. 2020), as well as the embodied energy in construction materials during manufacturing, construction, maintenance, repair, and demolition (Mohammed et al. 2013). In response to the effects of climate change, many governments have developed various sustainable construction strategies to achieve carbon neutrality in the building sector (Adel et al. 2021). The increasing use of renewable resources for electricity production consumed in buildings is one of the key factors in reducing greenhouse gas emissions.

Various approaches can be employed to assess the environmental impact of a building. At the building scale, Life Cycle Assessment (LCA) is one of the recognized scientific methods, even standardized internationally. It is currently the only scientifically valid approach for conducting an environmental assessment at the building level. It provides a quantitative analysis of environmental impacts throughout the building's life cycle. The majority of scientific studies on this subject rely on this method (Peuportier et al. 2006).

Life Cycle Assessment (LCA) was first conducted in 1969 by the Midwest Research Institute (MRI) on behalf of the Coca-Cola Company. The firm sought to obtain concrete data to guide its decision regarding the most suitable type of packaging for its products. However, due to the confidential nature of the data, this study was never made public (Hunt et al. 1996).

The oil crisis and the increasing frequency of ecological, natural, and industrial disasters—such as toxic clouds, hurricanes, cyclones, heatwaves, droughts, oil spills, and the Chernobyl catastrophe of the 1970s—contributed to the rise of energy efficiency assessment tools, often to the detriment of more holistic approaches such as Life Cycle Assessment (Bribian et al. 2009). The first public LCA database emerged in Switzerland under the name BUWAL (Jolliet et al. 2005).

In the early 1980s, discussions incorporating the entire life cycle of products began extending to the construction sector. However, a significant lack of scientific discourse and consultation on the subject was evident. Moreover, the reliability of results was often questioned, as they were frequently used for commercial purposes, undermining the credibility of LCA (Guinee et al. 1993). By the late 1980s, interest in LCA grew due to increasing concerns over solid waste management. The formal standardization process of LCA methodology commenced in the early 1990s.

At the international level, several organisations became actively involved in the development and standardisation of LCA. The most prominent among them include the Society of Environmental Toxicology and Chemistry (SETAC), the International Organization for Standardization (ISO 2006a), and the United Nations Environment Programme (UNEP) (Jolliet et al. 2005). During the 1990s, the first specialized LCA articles appeared in prestigious scientific journals such as Journal of Cleaner Production, Resources, Conservation and Recycling, International Journal of LCA, Environmental Sciences & Technology, and Journal of Industrial Ecology (Guinee et al. 2011). In 1997, ISO (2006a) published its first standard, ISO 14040, aimed at harmonising procedures. This standardization led to the development of a general methodology, making it easier to compare different studies.

The 21st century has been marked by an accelerated expansion of research into comprehensive life cycle assessment of goods and products. A growing number of scientific studies have been published, and interest in LCA applications for the construction sector continues to rise. In 2003, SETAC released a state-of-the-art review on LCA applied to construction and buildings, highlighting the differences between the general LCA methodology and its application in the building sector. This review also pointed out the lack of precision in ISO (2006a) standards concerning LCA for buildings. The standardization process has since continued under the leadership of two key organizations: ISO (2006a) and the European Committee for Standardization (CEN). In 2006, international standards (ISO,2006a, b) were further refined to more precisely define the general LCA methodology. Today, LCA is recognised as the most advanced and objective multi-criteria assessment tool for evaluating environmental impacts, extending to the scale of entire buildings (Reiter 2010).

In the 2010s, the use phase of a conventional building was responsible for approximately 60 to 90% of its total environmental impact, largely due to energy consumption for heating and cooling (Buyle et al. 2013). (Rossi et al. 2012) Conducted a study comparing the life cycle assessment (LCA) of an existing residential building constructed with two different building techniques to that of a metal-framed house in three European countries: Belgium, Portugal, and Sweden. Despite the variations in climate among these countries, the study found that the operational stage consistently had the most significant environmental impact across all cases.

Citherlet and Defaux (2007) highlighted the importance of carefully considering the construction and demolition phases of a building's life cycle, particularly when annual energy consumption falls below 150 MJ/m^2. The potential for material recycling was explored in Switzerland by Thormark (Thormark 2002, 2006), while (Blengini and Di Carlo 2010) examined the demolition of a 40-year-old apartment in Italy. Both studies emphasised that reuse offers greater benefits than recycling. (Erlandsson and Levin 2003) analysed the environmental advantages of renovating existing homes in Switzerland, concluding that renovation is generally an eco-friendly solution. However, urban regulations often impose constraints that prevent the implementation of all optimal measures. (Piderit et al.2019) investigated design strategies and technical specifications needed to achieve Nearly Zero-Energy Building (ZEB) standards in Chilean schools, emphasizing the necessity of updating national regulations to account for evolving climatic conditions.

In 2021, (Nematchoua et al. 2022) conducted research on residential buildings with the main goal of assessing, analysing, and proposing strategies for developing nearly zero-energy, low-emission, and cost-efficient housing on a global scale. Their findings demonstrated that incorporating heat pumps could decrease the costs associated with nine environmental impacts by approximately 8.7–13.1% over an

80-year lifespan compared to the initial expenditure. One of the major obstacles to understanding climate change at the neighbourhood scale has been the scarcity of consistent data on life-cycle carbon emissions and energy consumption. To address this gap, (Nematchoua et al. 2021) analysed and compared three neighbourhood types—urban, rural, and sustainable—adaptable to various global regions. Their study offered recommendations to mitigate carbon emissions and reduce energy consumption. The combination of large-scale building renovations with rooftop photovoltaic panel installations suggests that achieving carbon neutrality at the neighbourhood level by 2050 is a realistic target. Amphitheatres, as key elements of educational and social infrastructure, play an important role within the community and the educational sector. However, their construction, use, renovation, and demolition all have significant consequences on the environment, particularly in terms of greenhouse gas emissions, energy consumption, and waste management**.**

This research aims to assess the environmental impacts of Amphitheatre 1001 at the University of Yaoundé I throughout its entire life cycle. The core issue of this study lies in identifying and implementing solutions to reduce emissions associated with the environmental impacts of this amphitheatre over its lifespan. Furthermore, this study presents an original contribution to the scientific literature by offering one of the very first comprehensive Life Cycle Assessments applied to a large educational building in a tropical, high-occupancy context. While most existing LCA research remains concentrated in temperate or industrialised regions, this work addresses a critical gap by generating reliable, context-specific data for a developing country where environmental performance, resource constraints, and occupancy behaviours differ significantly from global standards. By combining dynamic thermal simulation with multi-criteria LCA through the PLEIADES platform, the study demonstrates an integrated methodological approach rarely used in tropical regions. Furthermore, the comparative analysis of multiple mitigation scenarios—mobility management, photovoltaic integration, rainwater harvesting, and building orientation—provides practical, replicable strategies for universities and public institutions seeking to reduce their environmental footprint. Beyond its local relevance, the findings contribute to the global effort to define sustainability pathways tailored to tropical climates, supporting more inclusive and geographically diverse environmental decision-making. Considering the objectives of this study and the comparison of different scenarios related to the building and its occupancy, the functional unit will be the number of occupants of the amphitheatre. The life cycle phases of the amphitheatre to be analysed are as follows: Construction usage phase, Renovation phase, and End-of-life phase. This study will assess the environmental impacts of Amphitheatre 1001, including factors such as mobility, the use of renewable energy, building orientation, and rainwater management on the amphitheatre's environmental footprint. These elements will be analysed from the construction phase to their end-of-life (landfill disposal), including the usage and renovation phases. The environmental impact categories to be evaluated in this study include: Greenhouse gas emissions (Global Warming Potential);Acidification (acid rain and soil degradation potential);Cumulative energy demand (total energy consumed throughout the life cycle); Water usage (volume of water consumed);Production of inert waste (non-recyclable waste);Depletion of abiotic resources (use of non-renewable materials); Eutrophication (nutrient pollution of water bodies); Photochemical ozone formation (smog production); Aquatic ecotoxicity (harmful effects on aquatic ecosystems); Radioactive waste production (nuclear by products); Human toxicity (adverse effects on human health); Odour emissions (impact on air quality and human comfort). These categories provide a comprehensive understanding of the environmental performance and areas for improvement in the amphitheatre's life cycle.

Materials and methods

In this section, we will first introduce the amphitheatre under study and describe the method used to evaluate its environmental impact. Next, we will detail the analysis tool employed, including the assumptions considered in the dynamic thermal simulation and the life cycle assessment of the amphitheatre. Finally, we will define the alternative scenarios to be examined, whose results will be analysed and compared in the following section to identify the most environmentally friendly option.

Selection of the amphitheatre and site description

For this study, we chose to model an existing amphitheatre based on its architectural plans, enabling the exploration of a series of alternative scenarios (see Fig. 1). Our focus is on Amphitheatre 1001, one of the largest at the University of Yaoundé I. This choice is justified by its size, high usage, and strategic role in university education, making it a relevant case study for assessing environmental impacts and proposing optimized solutions.

This figure illustrates Amphitheatre 1001, one of the largest lecture halls at the University of Yaoundé I, chosen for this study due to its scale and significant role in accommodating large numbers of students.

Fig. 1 Amphitheatre 1001 at the University of Yaoundé I

Fig. 2 Location of Amphitheatre 1001 at the University of Yaoundé I

Site description

Amphitheatre 1001 is one of the largest lecture halls at the University of Yaoundé I. It spans approximately 972.4 m^2 with a seating capacity of around 1000. The building is located at an altitude of 772.2 m in an urban zone, positioned at 3°51′30.95" North latitude and 11°30′18.03" East longitude.

The amphitheatre consists of: A lecture hall of about 905.3 m^2; A technical room of approximately 9.2 m^2, responsible for the amphitheatre’s sound system; Two offices, one for the physics club (14.6 m^2) and the other for the biology club (15.1 m^2); A room designated for accommodation, measuring about 16.1 m^2; Toilets that have been repurposed into a storage area of about 8.3 m^2; An additional small storage room of approximately 3.8 m^2. Figure 2 illustrates the layout and structure of Amphitheatre 1001.

Life Cycle Assessment (LCA) is a multi-stage and multi-criteria environmental evaluation method used to quantify the impacts of a product, service, process, or structure throughout its life cycle: from raw material extraction to end-of-life treatment. This approach provides the most comprehensive and multifaceted assessment of environmental impacts. It is standardized and recognized by international norms (ISO 2006a, b).

Tools

The software used for this study is “PLEIADES”, a suite of tools developed by the Centre for Energy Efficiency of Systems at Mines ParisTech (AZUBA, 2024). Historically, this software is the result of a merger of three separate tools: ALCYONE, COMFIE-PLEIADES, and NOVAEQUER.

The PLEIADES suite is widely employed by numerous international research laboratories and has been extensively validated by the scientific community (AZUBA, 2024). It is a robust and recognized tool for conducting energy and environmental efficiency analyses, ensuring the reliability and accuracy of the findings in this study. Overall, the PLEIADES software is structured into six main components, described as follows:

(i) Pleiades Library: This module provides access to the general library of PLEIADES, containing data and resources essential for the software’s functionality.
(ii) Pleiades Modeller: Designed to simplify building data entry, this component allows users to: Define the building’s geometric parameters; Assign thermal properties to individual walls; Perform zoning; Quickly assign usage scenarios and calculation parameters for various analyses offered by PLEIADES.
(iii) Pleiades BIM: This tool enables users to: Import files in gbXML or IFC 4 formats; Convert them into Pleiades Éditeur projects; Enhance the thermal representation (e.g., zoning, scenarios) and initiate calculations. It retrieves elements such as rooms, walls, windows, and compositions from the building model and displays a three-dimensional representation.
(iv) Pleiades Editor: This module facilitates the complete entry of a project in a tree-structured format, enabling users to perform various calculations, such as STD/SED (Thermal and Energy Simulations); RE (2020) (Compliance with France’s 2020 energy regulations).
(v) Pleiades Result: The results generated from calculations initiated in Modeleur, Éditeur, or Pleiades BIM can be viewed and analysed using this component.
(vi) Pleiades ACV: This module focuses on Life Cycle Assessment (LCA), evaluating the environmental impacts at the building or neighbourhood scale.

Modelling of the amphitheatre

General construction data

To initiate the modelling process, the default composition of walls, doors, windows, surface states, and thermal bridges is first entered into Pleiades Modeller. When a wall or joinery element does not match the default composition or geometric dimensions encoded in the software, it is manually modified to reflect the actual characteristics of Amphitheatre 1001. This customisation ensures that the model accurately represents the building’s physical and thermal properties, enabling precise analysis and reliable simulation results. In addition to material composition, the building’s construction characteristics are explicitly considered in the modelling process. Amphitheatre 1001 is a masonry building constructed primarily with concrete blocks, covered with cement-based internal and external coatings, and supported by reinforced concrete slabs for the floors. The roofing system consists of a light metal structure with corrugated roofing sheets, a common construction technique used in tropical regions for its durability and ease of maintenance. Openings include single-glazed metal-frame windows and metal doors, consistent with typical educational infrastructure in Cameroon.

From a geometric and spatial perspective, the amphitheatre has a rectangular floor plan, with its longest façades oriented North–South in the current configuration. This orientation influences solar exposure but does not affect heating/cooling loads, as the building is naturally ventilated and operates without mechanical air-conditioning systems. Overall, integrating these construction details—materials, envelope composition, structural elements, and orientation—into the Pleiades model ensures that the simulations reflect realistic thermal behaviour and environmental performance throughout the building’s life cycle.

Wall composition

In Pleiades Bibliothèque, the materials and construction elements, along with their thicknesses, properties, and any potential thermal bridges, are entered. The various wall compositions used in this project are detailed in Table 1. This table includes the following parameters for each material: Thickness (e), Density (ρ), Thermal Conductivity (λ) and Thermal Resistance (R).

Table 1 Wall composition of the building

	Component	e (cm)	λ (W/(m.K))	ρ (kg/m^3)	R ((m^2.K)/W)
Exterior wall/Interior	Exterior coating	1.5	1.150	1700	0.01
	concrete block	20.0	1.053	1300	0.19
	Interior coating	1.5	1.150	1700	0.01
Low floor	concrete slabs	16.0	1.231	1300	0.13
	Heavy concrete	4.0	1.750	2300	0.02
	Mortar	4.0	1.150	2000	0.03
	Tiling	1.0	1.700	2300	0.01

Table 2 Surface properties of the building

		Emissivity (ε)	Absorptivity (α)	Reflectivity (ρ)
External face	Smooth grey/orange colour	0.90	0.40	33%
Floor	Concrete (tiles)	0.88	0.70	30%
External roof	Smooth brown colour	0.90	0.70	20%
Internal face	Smooth grey colour	0.90	0.40	33%
Ceiling	White paint	0.91	0.20	80%

Table 3 Characteristics of doors and windows

	U$_f$ (W/(m^2.K))	U$_w$ vertical (W/(m^2.K))	U$_w$ horizontal (W/(m^2.K))	TI	Solar factor S$_w$
Metal door	5.8				0,22
Glazed metal window	7	6.439	6.439	0	0.594
Window with simple openings	2.4	0	0	1	0.5994

Table 2, Surface Properties of the Building**,** describes the emissivity (ε), absorptivity (α), and reflectivity (ρ) of the surface finishes used in the building. These properties are crucial for managing solar radiation interactions and optimizing the thermal performance of the amphitheatre.

Table 3 shows characteristics of doors and windows, which can be structured based on standard values typically provided by software like PLEIADES. It includes thermal transmittance (Uf, Uw vertical, Uw horizontal), solar factors (Sw), and light transmission factors (TI).

Meteorological data

Meteorological data constitute a critical input for this study because they govern the thermal behaviour of the amphitheatre, modulate solar gains, and condition its overall energy performance throughout the life cycle. The building is located in Yaoundé, Cameroon, a city characterized by a humid equatorial (Guinean) climate marked by persistently high relative humidity, abundant rainfall ranging from 1600 to 2000 mm per year, low wind speeds (typically 1–2 m/s), moderate solar irradiation averaging 4.5–5.0 kWh/m^2/day, and relatively stable temperatures between 22 °C and 25 °C with limited seasonal variation. These climatic conditions justify the absence of heating needs and indicate that thermal comfort is primarily driven by natural ventilation, occupancy loads, and solar exposure rather than active HVAC systems. Meteorological data were sourced from the Yaoundé City meteorological station (ID 64950/FKYS), as they are the closest and most representative of the local microclimate. Since these data are not natively integrated into PLEIADES, they were processed through the STD COMFIE Météocalc utility and converted into Test Reference Year (TRY) format to ensure compatibility. The dataset includes hourly ambient temperatures, global and diffuse horizontal radiation, direct normal radiation, relative humidity, cold-water supply temperature, and wind characteristics. A correction for altitude was applied, as the amphitheatre sits at approximately 772 m, slightly above the station's 751 m; PLEIADES adjusts temperatures automatically using a lapse rate of − 0.6 °C per 100 m. The exact geographical coordinates of the project were also entered to ensure accurate simulation of solar paths and climatic influences relevant to dynamic thermal modelling and the subsequent LCA.

Fig. 3 Building 3D modelling

Table 4 Building thermal areas

N°	Zones	Area (m^2)	Volumes (m^3)
1	Classroom	882.58	10,386.48
2	Office 1	15.07	37.68
3	Technical room	9.23	23.06
4	Bedroom	16.11	40.26
5	Office 2	14.64	36.60
6	Store 1	3.77	9.43
7	Store 2	8.33	20.82
8	Room 1	10.86	125.83
9	Room 2	11.81	131.98

3D Modelling

After entering the data mentioned above, we proceed with the three-dimensional (3D) modelling of the amphitheatre. This process is based on the architectural plans and additional data collected during an on-site survey. The modelling involves defining the walls, floors, roofs, and openings. The geometry of the building and its actual openings have been accurately replicated to ensure a faithful representation of the structure(Fig. 3).

This precise 3D modelling is essential for simulating the building's thermal and energy performance under realistic conditions.

Building simulation process

Thermal zone

After modelling this room, we defined the thermal zones and their occupation scenario, with the objective of achieving the thermal dynamic simulation. Globally, we created 09 thermal zones as describe in the Table 4.

Occupation scenario

Based on the specific usage of each thermal zone, the various occupancy scenarios for the amphitheatre were defined:

- *The "Classroom" zone* is primarily reserved for undergraduate students at Levels 1, 2, or 3. Considering the significant number of students across these levels and the seating capacity of this zone, a thorough review of the schedules for the past two academic years (2021/2022, 2022/2023) as well as the current academic year revealed that classes take place from Monday to Friday, beginning at 7:00 AM and ending at 9:59 PM. On average, the classroom accommodates approximately 1,450 students.
- *The "Office 1" zone* is a small room used as the office of the Biology Club in the Faculty of Sciences. It typically accommodates an average of four (4) people from Mon-

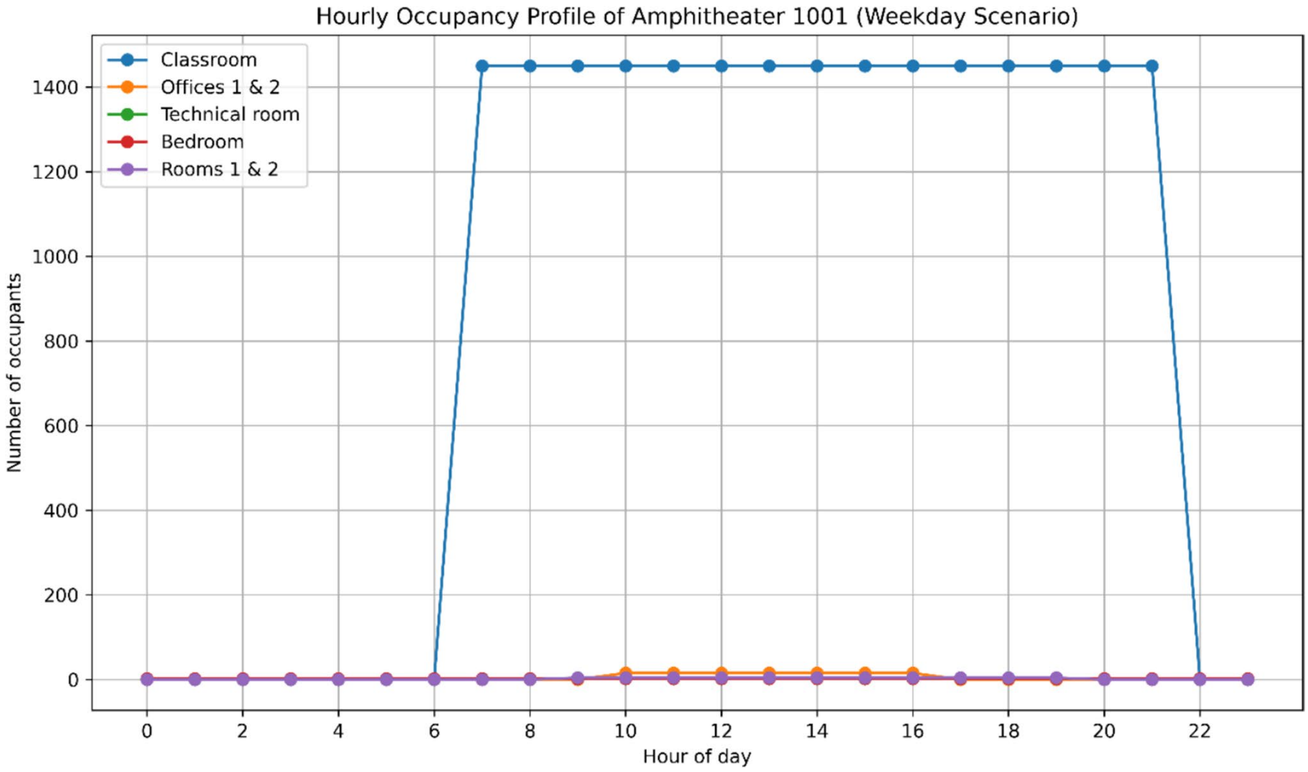


Fig. 4 Building occupancy scenario

day to Friday and two (2) people on Saturdays during hours that will be specified later in this work.

- *The "Office 2" zone* is similar to "Office 1" and is used as the office of the Physics Club in the Faculty of Sciences, with identical occupancy patterns.
- *The "Technical Room" zone* is responsible for the sound system operations for the classroom during the week. It houses, on average, two (2) individuals: one technician and one student.
- *The "Bedroom" zone* serves as accommodation and is permanently occupied by two (2) individuals.
- The "Storage Room 1" zone was originally designed as restrooms but has been converted into a small storage area.
- The "Storage Room 2" zone is a very small storage area.
- The "Room 1" and "Room 2" zones are very small spaces that are occasionally used by a few students as a mini-library (see Fig. 4).

Set point temperature scenario

Since the amphitheatre is located in a tropical equatorial climate, no mechanical heating systems is installed in the building; therefore, no temperature-set point control scenario are applied. However, to ensure consistency in the computation of energy consumption within the dynamic simulation, several assumptions were made. The model assumes that indoor thermal conditions are governed exclusively by natural ventilation through openings, internal heat gains from occupants and equipment, and the interaction with the building envelope. Consequently, energy consumption is limited to lighting and plug-loads (computers, projectors, and audio systems), with no electricity considered for space heating or air-conditioning. This assumption aligns with observed real operating conditions on site and ensures that thermal loads in the simulation reflect only passive environmental responses and occupancy-driven internal gains, rather than mechanically regulated temperatures.

Ventilation

The building under study is not equipped with a Mechanical Ventilation System (MVS). Instead, it features numerous large windows, and air renewal within the building occurs through these windows.

Life cycle assessment process

The LCA conducted in this study strictly followed the principles and methodological framework defined by ISO 14040 and complied with the requirements of ISO 14044

(ISO, 2006a, b). These standards guided the definition of the goal and scope, system boundaries, life cycle inventory analysis, impact assessment, and interpretation phases. The application of these international standards ensures the transparency, consistency, and reproducibility of the LCA results and allows meaningful comparison with other building-scale LCA studies reported in the literature. To conduct the LCA of the amphitheatre and assess the twelve (12) associated environmental impacts, the Pleiades LCA software was used. This software relies on a simulation engine based on a detailed methodology developed by the Centre for Energy Efficiency of Mines ParisTech. This methodology incorporates the Ecoinvent environmental database, which provides information on the manufacturing of materials and the various processes included in the system, such as energy production, water supply, and waste treatment. For this study, version 3.11 of the Ecoinvent database was used. This database includes life cycle inventory data at an international industrial scale, covering various sectors such as energy supply, resource extraction, material provision, chemicals, metals, agriculture, as well as waste management and transportation services.

In this study, it is assumed that most materials are inert waste at the end of their life cycle. Additionally, a 5% surplus of materials used on-site is considered. This surplus accounts for unused materials, broken items, and offcuts. We provide default lifespans for the various building components, as these were essential for calculating the environmental impacts of the renovation phase. The lifespan of the finishes is set at 10 years, 20 years for specific equipment, and 30 years for doors and glazing. Structural and insulating materials are assumed to have a lifespan equal to that of the building, i.e., 80 years (ISO 2006a, b). Transportation distances are set at 100 kms from the production site to the construction site, and 11 kms from the site to the landfill.

Using version 3.11 of the Ecoinvent database, we obtained life cycle inventories for energy, materials, waste treatment, transportation, products, electronics, and building machining.

For each component used, we can determine:

- The typical lifespan of the component in question.
- The environmental data entry is to be associated with each phase of the material's life cycle. The proposed associations are the default associations provided by the software.

In the 'Project' tab, we begin by entering the geographical location of the amphitheatre. It is located at the University of Yaoundé I, where seismic activity is very low. The building sits at an altitude of 772 m, and its geographical coordinates are as follows: latitude N 3°50′29" and longitude E 11°29′31".

The amphitheatre consists of a lecture hall with an average occupancy of one thousand four hundred fifty (1450) people, two (02) offices, and two (02) small extension rooms, each averaging four (04) people. It also includes a technical room for two (02) people and a small room for two (02) people as well.

The completion of a full life cycle assessment (LCA) for the building is contingent upon entering data for the following modules: energy, water, waste, and transportation.

Scenarios

Initial scenario

(i) Energy Data

To ensure the most accurate determination of the impact of electricity consumption, we input the Cameroonian electricity mix in the "Energy" tab. It is as follows: 62% from hydroelectric power plants, 14% from gas power plants, 24% from thermal power plants, and 0.1% from solar power plants (Rapport annuel 2020).

(ii) Water

For water consumption, no description of water production equipment is necessary, as the amphitheatre does not have any dedicated equipment for this purpose. Rainwater harvesting systems are also not considered.

Since the amphitheatre is intended for educational and research purposes, we assume a water consumption of two (02) litres per person per day, with zero (00%) per cent for hot water (ECS) for the lecture hall, the two offices of the Physics and Biology clubs, the technical room, and the two extension rooms. For the last room, which is used for accommodation, the water consumption is as follows: seventy (70) litres of cold water per person per day and thirty (30) litres of hot water (ECS) per person per day as reported by (ADEME 2014), which indicates an average daily consumption of approximately 100 L per person, around 30% of which corresponds to hot water use."

(iii) Waste

The selective sorting of certain waste materials is also considered in the calculation of the building's life cycle assessment (LCA). In Cameroon, the sorting rates are 72.71% for glass and 43% for paper and cardboard (Enterprise colonials 2024). This proportion of waste will therefore be considered as recycled and not sent to landfill. According to Cameroonian statistics, 30% of the 850 g of daily household waste per person is sent for incineration, with a recovery efficiency of 5%. The distances from the site to the landfill for household waste are 11 km to the incinerator and recycling facilities.

(iv) Transport

The mobility component plays a significant role in this study. Therefore, the environmental impact of the daily commuting of the building's occupants is calculated. We assume that 90% of the occupants commute daily. This implies that 10% of the amphitheatre's occupants are students who either use bicycles or walk. The amphitheatre is located in an urban area, and the commute distances from home to the amphitheatre are covered by car or public transportation. These commutes occur five (05) days a week, for approximately 48 weeks per year. Once all this information is input, the life cycle assessment (LCA) calculation of the amphitheatre can be initiated. The results will be analysed and discussed in the following section.

Mobility scenario

This section focuses on the impact of mobility on the environmental footprint of the amphitheatre. In the initial scenario, the site is located in an urban environment, and a significant reliance on automobiles is observed for daily commutes. A comparison will be made between this scenario and a second one, where the site remains urban, but 80% of students commute by bicycle or on foot. The remaining 20%, considered either students living at a greater distance from the university or those with mobility impairments, rely on cars or public transportation.

Photovoltaic solar energy utilization scenario

In this section, we will assess the impact of installing photovoltaic solar panels on the building's environmental footprint. In the initial scenario, all electricity consumption was sourced from the Cameroonian electrical grid, and the associated production impacts were considered. In the new configuration, a photovoltaic system is installed on the roof of the amphitheatre, with panel coverage equivalent to two-thirds (2/3) of the roof's surface area. It is important to note that the building uses electricity primarily for lighting and to power certain devices, such as laptops, phones, projectors, and audio amplifiers. The installed system consists of monocrystalline photovoltaic panels, which are mounted on supports on the roof. The panels are inclined at 35°, the optimal angle for the city of Yaoundé. A dynamic thermal simulation of the new scenario is conducted, followed by a complete life cycle assessment (LCA) of the building.

Combined scenario (Mobility + Photovoltaic solar energy utilization)

This scenario incorporates the mobility and photovoltaic solar panel utilization scenarios described earlier.

Impact of rainwater management

In our initial scenario, no rainwater harvesting systems were considered, and there was no separate drainage network. As a result, all rainwater was directed into the wastewater system.

In this study, we examine a scenario that integrates rainwater management by implementing a rainwater harvesting system. The goal is to divert as much rainwater as possible from the wastewater network to a separate drainage system. This aims to relieve water treatment facilities and utilize the harvested rainwater for the building's water needs throughout its lifecycle. To achieve this, we will establish a system designed to capture 90% of the rainwater through storage tanks or ditches.

Impact of orientation on the environmental performance of the amphitheatre

In this section, we will investigate the effect of the building's orientation on the results of the Life Cycle Assessment (LCA). In our initial scenario, the building is positioned such that its longitudinal facades are oriented to the north and south. This scenario will be referred to as "0° orientation." We will then test other orientations by rotating the building layout by 45°, 90°, 135°, and 180°. For each of these orientations, we will conduct a dynamic thermal simulation and an environmental impact analysis of the building. Methodological workflow is presented in Fig. 5.

This flowchart illustrates the sequential methodological stages followed in the study, beginning with the selection and geometric modelling of Amphitheatre 1001, followed by dynamic thermal simulation in PLEIADES using local meteorological and occupancy data. The workflow then proceeds to the Life Cycle Assessment setup in accordance with ISO (2006a, b) guidelines, using the Ecoinvent 3.11 database for life cycle inventories. After defining the baseline scenario, five alternative scenarios (Mobility, Photovoltaic Solar Energy, Mobility+PV, Rainwater Management, and Orientation) were modelled. The environmental impacts were evaluated across 12 categories, and the scenarios were subsequently compared

Fig. 5 Methodological workflow for the life cycle assessment (LCA) of Amphitheatre 1001

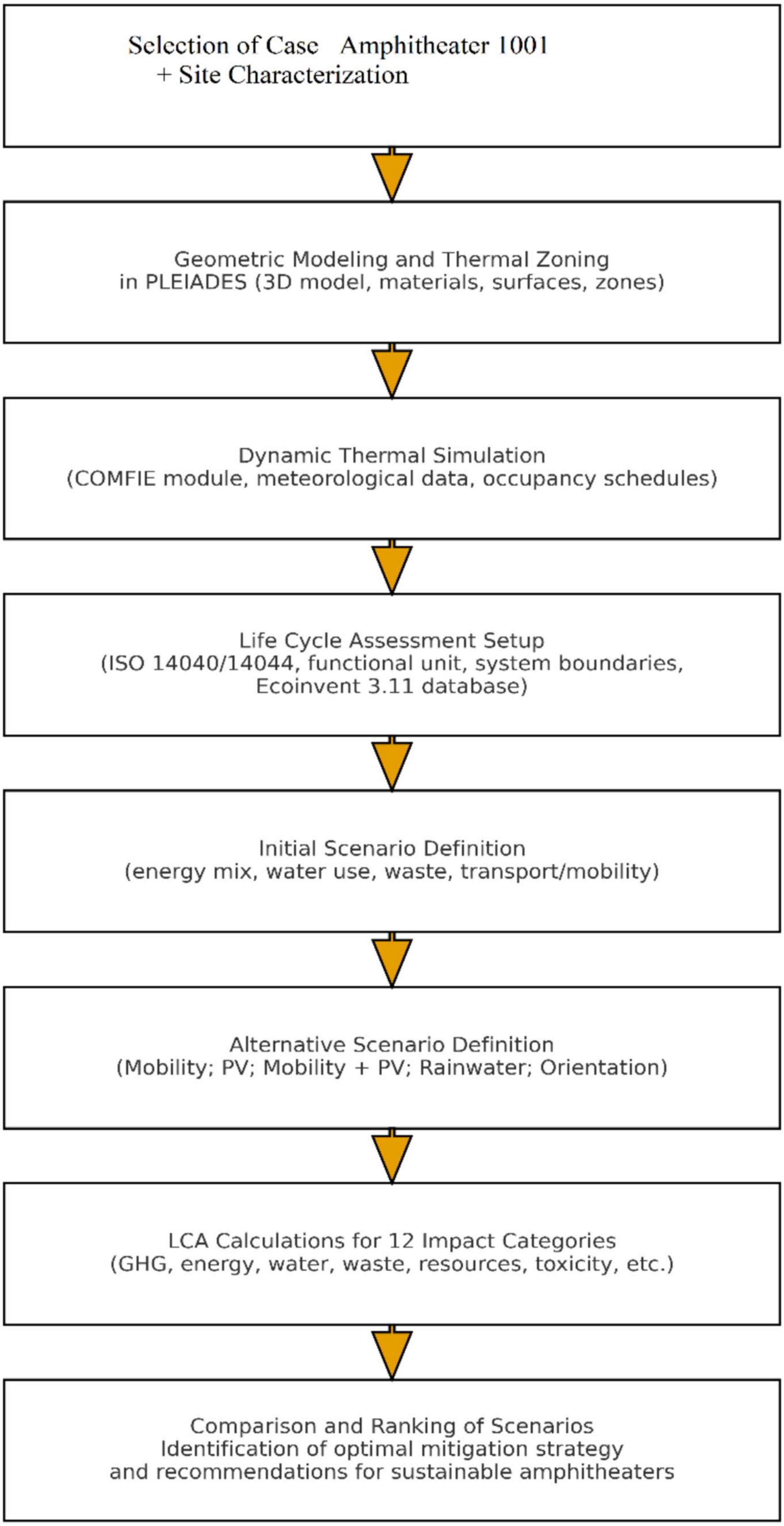


Table 5 Detailed results of the life cycle assessment of Amphitheatre 1001 at the University of Yaoundé I in terms of calculated impacts: initial scenario (in functional unit & in percentage)

Impact	Construction	Operational	Renovation	End of life	Total
Greenhouse effect in t CO2 eq.(%)	1068.63 (8.52%)	11,452.07 (91.29%)	19.67 (0.16%)	4.82 (0.04%)	12 545.19 (100%)
Acidification in kg SO2 eq.(%)	8055.88 (4.81%)	159,115.27 (95.08%)	119.71 (0.07%)	55.11 (0.03%)	167 345.97 (100%)
Cumulative energy demand in GJ(%)	86,465.84 (7.37%)	1,086,264.22 (92.57%)	613.26 (0.05%)	78.84 (0.01%)	1 173 422.16
Water used in m^3(%)	14,573.48 (1.27%)	1,134,992.88 (98.68%)	518.60 (0.05%)	36.98 (0%)	1 150 121.94
Inert waste produced in t(%)	66.26 (0.03%)	227,083.23 (99.53%)	56.48 (0.02%)	945.53 (0.41%)	228 151.50
Abiotic resource depletion kg E-15(%)	0 0%	12.98 100%	0	0	12.98
Eutrophication In kg PO4 eq.(%)	606.81 3.70%	15,773.77 96.19%	9.49 0.06%	8.62 0.05%	16 398.69
Photochemical ozone production in kg ethylene eq.(%)	8870.51 10.70%	73,950.09 89.17%	54.03 0.07%	59.90 0.07%	82 934.54
Aquatic ecotoxicity m^3(%)	177,081,725.94 22.83%	598,062,170.36 77.10%	422,078.74 0.05%	158,323.02 0.02%	775 724 298.05
Radioactive waste dm^3(%)	4.36 0.28%	1539.58 99.63%	1.03 0.07%	0.29 0.02%	1 545.27
Human toxicity kg(%)	12,915.70 2.14%	591,077.94 97.78%	440.98 0.07%	66.25 0.01%	604 500.87
Odour (Mm^3 air)	947.31 2.39%	38,623.87 97.49%	42.76 0.11%	5.43 0.01%	39 619.37
Average percentage	5.34%	94.54%	0.06%	0.06%	100.00%

and ranked to identify the optimal mitigation strategy for improving the amphitheatre's environmental performance.

Results and discussion

The previous section provided a detailed description of the study building, an overview of the materials and methods employed to efficiently conduct the Life Cycle Assessment (LCA), and a discussion of several alternative scenarios. The present section is dedicated to presenting and discussing the results obtained from the various simulations.

Validation of the life cycle assessment results for Amphitheatre 1001 at the University of Yaoundé I

According to the Architecture and Climate Unit at UCL, a passive house ($0 \leq 15$ kWh/m^2.year) with a lifespan of 50 years emits between 8.3 and 15.3 kgCO_2eq/m^2.year (University College London (UCL) 2018). In our initial scenario, Amphitheatre 1001 at the University of Yaoundé I qualifies as a passive building, as its net heating energy demand is zero ($0 \leq 15$ kWh/m^2.year). Furthermore, as explained in reference (University College London (UCL) 2018), over 90% of greenhouse gas emissions and other environmental impacts occur during the operational phase. The total CO_2 emissions calculated in this study amount to approximately 14.05 kgCO_2eq/m^2.year. Since 14.05 kgCO_2eq/m^2.year falls within the standard range (14.05 kgCO_2eq/m^2.year < 15.3 kgCO_2eq/m^2.year), we conclude that the primary energy consumption and emissions per square meter are within the acceptable limits.

Initial scenario

Table 5 presents a detailed overview of the environmental impacts resulting from the Life Cycle Assessment (LCA) of Amphitheatre 1001 at the University of Yaoundé I over a period of 80 years, along with the percentage contribution of each impact relative to the total impact. The results presented represent the sum of the impacts across the four phases of the building's life cycle analysis: construction, operation, renovation, and deconstruction.

The analysis of the average contributions across twelve (12) environmental impact categories reveals that the operational phase is the most significant stage of the life cycle, accounting for an average of 94.54% of the total environmental impacts. In contrast, the construction, renovation, and demolition phases contribute 5.34%, 0.06%, and 0.06%, respectively.

A study of the various sources of greenhouse gas emissions throughout the building's life cycle reveals that: Firstly, the operational phase is the primary contributor, accounting for 91.29% of total greenhouse gas emissions. Within this phase, emissions are predominantly generated by waste (34.39%), which is largely due to the high occupancy of the auditorium. This is followed by transportation

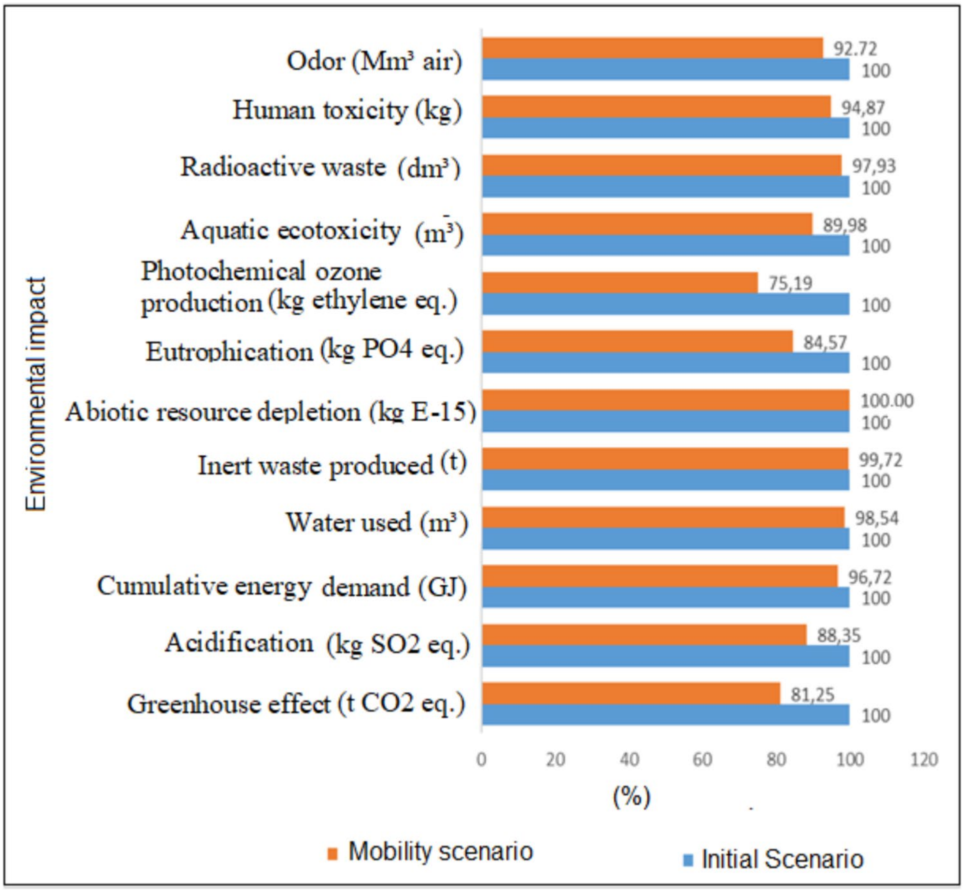


Fig. 6 Comparative diagram of the environmental impacts of the "initial" and "mobility" scenarios (functional unit: number of occupants)

(30.92%), electricity consumption (24.52%), specific electricity use (9.33%), water consumption (0.75%), and finally, hot water usage, which accounts for only 0.09% of emissions. Secondly, the construction phase contributes 8.52% of the total greenhouse gas emissions over the auditorium's entire life cycle. The primary sources of emissions in this phase include the roof (75.32%), façades (10.91%), ground floor slab (9.08%), partitions (2.29%), as well as doors (0.16%) and windows (0. 08%). Finally, the renovation and deconstruction phases have minimal impact, accounting for 0.16% and 0.04% of CO_2 emissions, respectively. Similar to greenhouse gas emissions, the operational phase remains predominant, accounting for 92.57% of the total cumulative energy demand. This dominance is primarily due to waste, along with electricity consumption (8.82%) and transportation (5.33%). In contrast, water contributes only 0.27%.

Mobility scenario

Figure 6 shows the comparison between the environmental impacts of the initial scenario and the mobility scenario.

It is evident that mobility has a significant impact on the environmental footprint of amphitheatre 1001. After applying the proposed scenario, all environmental impact indicators were reduced. Five (05) out of twelve (12) indicators showed a reduction of over 10%(Table 6).

First, across the entire life cycle of the amphitheatre, there is an observed reduction of approximately 24.81% in photochemical ozone production. This decrease is primarily due to the reduced use of transportation during the operational phase. Indeed, nitrogen oxides, whose main source is fuel combustion, transform into photochemical ozone under sunlight. In this scenario, the reduction in car usage helps avoid about 24.81% of this indicator's production throughout the amphitheatre's life cycle.

Regarding the greenhouse effect, a similar trend is observed. Due to the reduction in transport-related emissions during the operational phase, there is a reduction of about 18.75% in greenhouse gas emissions over the amphitheatre's entire life cycle. However, the construction, renovation, and deconstruction phases are not impacted by this scenario. The reduction in car usage also affects acidification, with a reduction of about 11.65% in this indicator throughout the amphitheatre's life cycle. Human toxicity is reduced by 5.13%, as less fuel and fossil resources are consumed, which also reduces pollution, responsible for numerous health issues.

Table 6 The environmental impacts of the amphitheatre and the reduction rate of the environmental impacts after considering mobility factors

Impact	Initial Scenario	Mobility Scenario	Difference
Greenhouse effect (t CO2 eq.)	12,545.19	10,192.82	18.75%
Acidification (kg SO2 eq.)	167,345.97	147,846.87	11.65%
Cumulative energy demand (GJ)	1,173,422.16	1,134,956.05	3.28%
Water used (m^3)	1,150,121.94	1,133,331.72	1.46%
Inert waste produced (t)	228,151.50	227,507.65	0.28%
Abiotic resource depletion (kg E-15)	13	12.98	0.00%
Eutrophication (kg PO4 eq.)	16,398.69	13,868.30	15.43%
Photochemical ozone production (kg ethylene eq.)	82,934.54	62,361.56	24.81%
Aquatic ecotoxicity (m^3)	775,724,298.05	697,989,096.61	10.02%
Radioactive waste (dm^3)	1,545.27	1,513.24	2.07%
Human toxicity (kg)	604,500.87	573,513.21	5.13%
Odour (Mm^3 air)	39,619.37	36,734.42	7.28%

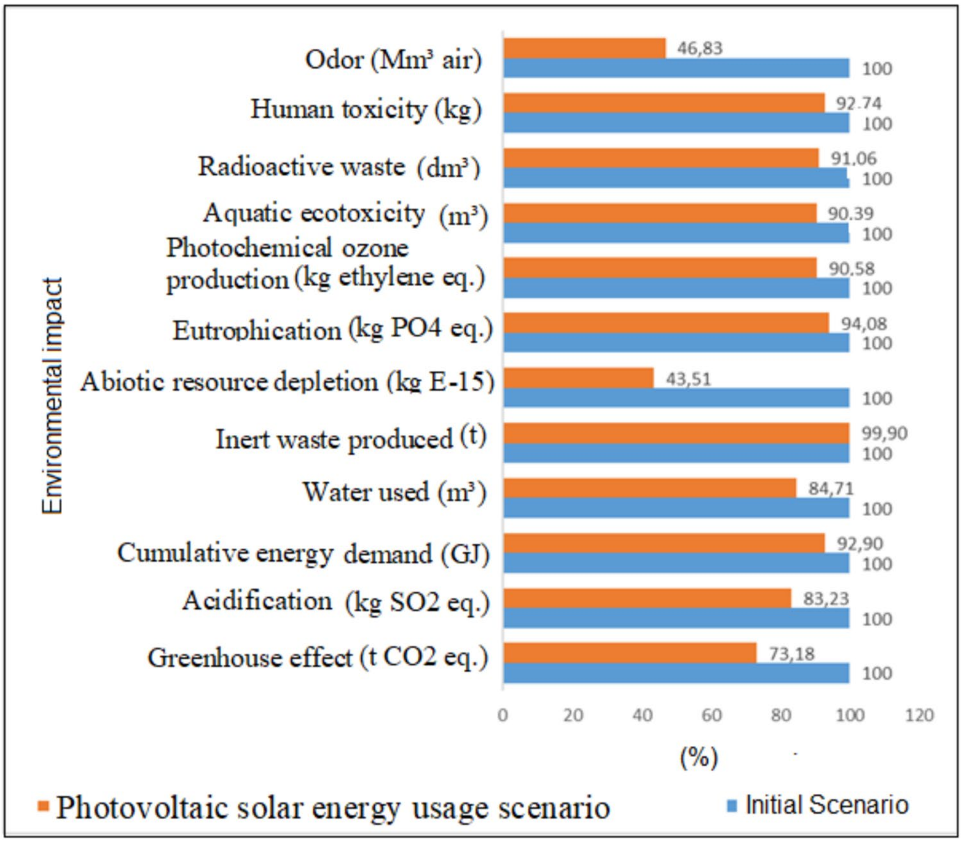


Fig. 7 Comparative diagram of the environmental impacts of the "initial" and "Photovoltaic solar energy usage" scenarios (functional unit: number of occupants)

Lastly, additional reductions are observed as follows: 15.43% in eutrophication, 10.02% in aquatic ecotoxicity, 7.28% in odours, 3.28% in cumulative energy demand, 2.07% in radioactive waste, 1.46% in water usage, and 0.28% in inert waste production.

The mobility scenario would significantly reduce the environmental impacts of the amphitheatre over its entire life cycle, as the amphitheatre is frequented by a large number of people who require transportation to access it daily.

Renewable energy use scenario

After the dynamic thermal simulation of the renewable energy usage scenario, the electricity consumption and production are calculated. The amphitheatre consumes an average of 36,763 kWh of electricity annually. The photovoltaic solar panels, on the other hand, produce an average of 185,230 kWh per year.

Table 7 Variation of the LCA results for the University of Yaoundé I Amphitheatre 1001 based on the photovoltaic solar energy usage scenario

Impact	Initial scenario	Solar energy usage scenario	Difference
Greenhouse effect (t CO2 eq.)	12,545.19	9,181.00	26.82%
Acidification (kg SO2 eq.)	167,345.97	139,284.76	16.77%
Cumulative energy demand (GJ)	1,173,422.16	1,090,077.36	7.10%
Water used (m^3)	1,150,121.94	974,237.39	15.29%
Inert waste produced (t)	228,151.50	227,923.03	0.10%
Abiotic resource depletion (kg E-15)	13	5.65	56.49%
Eutrophication (kg PO4 eq.)	16,398.69	15,427.25	5.92%
Photochemical ozone Production (kg ethylene eq.)	82,934.54	75,126.12	9.42%
Aquatic ecotoxicity (m^3)	775,724,298.05	701,214,538.64	9.61%
Radioactive waste (dm^3)	1,545.27	1,407.08	8.94%
Human toxicity (kg)	604,500.87	560,629.07	7.26%
Odour (Mm^3 air)	39,619.37	18,555.51	53.17%

It is evident that the electricity production from the installation of photovoltaic solar panels on two-thirds of the amphitheatre's roof greatly exceeds the annual electricity consumption of the amphitheatre due to lighting. With this electricity production, it is possible to power the lighting of approximately four (04) amphitheatres of the same configuration. The reduction rate of the various environmental impacts of the amphitheatre over its entire life cycle is detailed in Fig. 7 and Table 7.

We observe that the use of photovoltaic solar panels has a significant impact on the environmental footprint of the amphitheatre. The most affected impacts are abiotic resource depletion, odour, and the greenhouse effect, with reduction rates of 56.49%, 53.17%, and 26.82%, respectively, over the entire life cycle of the amphitheatre. This substantial reduction in abiotic resource depletion (56.49%) is primarily due to the use of photovoltaic solar panels. Indeed, the LCA results of the initial scenario show that the construction, renovation, and deconstruction phases have no impact on abiotic resources. The only phase showing an impact is the usage phase. These impacts are mainly due to electricity and domestic hot water consumption. Waste, on the other hand, has a negative impact.

However, after applying the photovoltaic solar energy usage scenario, a significant reduction in this impact is observed during the usage phase. On the other hand, the use of photovoltaic solar energy has a negative impact on the construction and renovation phases (due to the equipment used in the production of solar panels). These negative impacts are largely offset by the positive impacts of the usage phase. The initial scenario shows a total abiotic resource depletion impact of 12.98 (kg E-15) over the entire life cycle of the amphitheatre, whereas the photovoltaic solar energy scenario has a total impact of 5.65 (kg E-15), resulting in a reduction percentage of approximately 56.49%. The significant reduction in the "greenhouse effect" impact (26.82%) is primarily due to the usage phase. Indeed, photovoltaic solar energy is a clean energy source. Its use reduces greenhouse gas emissions by 3388.97 tCO2eq (29.59%) throughout the amphitheatre's life cycle during the usage phase. However, the construction and renovation phases have a negative impact of 100.58% and 194.46%, respectively, due to the manufacturing and maintenance of the photovoltaic solar panels.

The "odour" impact shows a reduction of 53.17% over the entire life cycle of the amphitheatre. Unlike the use of thermal power plants and gas plants, which are part of the electricity generation mix in Cameroon and emit significant amounts of odour (due to electricity production), the use of photovoltaic solar panels helps reduce odour emissions by 21,083.38 Mm3 air (54.59%) throughout the amphitheatre's life cycle during the usage phase. However, similar to the "greenhouse effect" impact, the construction and renovation phases have a negative impact of 101% and 134%, respectively, due to the transportation of solar panels during the construction and renovation phases. Nonetheless, the positive impacts from the usage phase offset these negative ones.

The cumulative energy demand also shows a considerable reduction, decreasing by 7.14% over the entire life cycle of the amphitheatre. Indeed, the results of the LCA for the initial scenario show that the cumulative energy demand of the amphitheatre throughout its life cycle is approximately 1,173,422.16 GJ. The cumulative energy demand due to electricity production and consumption is about 95,862.79 GJ, or 8.17% of the total cumulative energy demand.

Table 8 Variation of the LCA results for Amphitheatre 1001 of the University of Yaoundé I, based on the mobility scenario and photovoltaic solar energy usage scenario

Impact	Initial scenario	Mobility Scenario + Photovoltaic Solar Energy Usage	Difference (%)
Greenhouse effect (t CO2 eq.)	12,545.19	6,828.63	45.57
Acidification (kg SO2 eq.)	167,345.97	119,785.65	28.42
Cumulative Energy Demand (GJ)	1,173,422.16	1,051,611.25	10.38
Water Used (m^3)	1,150,121.94	957,447.16	16.75
Inert Waste Produced (t)	228,151.50	227,279.18	0.38
Abiotic Resource Depletion (kg E-15)	13	5.65	56.49
Eutrophication (kg PO4 eq.)	16,398.69	12,896.87	21.35
Photochemical Ozone Production (kg ethylene eq.)	82,934.54	54,553.13	34.22
Aquatic Ecotoxicity (m^3)	775,724,298.05	623,479,337.20	19.63
Radioactive Waste (dm^3)	1,545.27	1,375.06	11.01
Human Toxicity (kg)	604,500.87	529,641.41	12.38
Odor (Mm^3 air)	39,619.37	15,670.55	60.45

However, the use of photovoltaic solar energy reduces the cumulative energy demand by 83,806.78 GJ, or 7.14%, throughout the amphitheatre's life cycle during the usage phase. This results in a reduction of approximately 87.42% of the cumulative energy demand due to electricity. On the other hand, this energy use has a negative impact on the construction and renovation phases (due to solar panel transportation). These negative impacts are minimal and are compensated for by the positive impacts from the usage phase.

A significant reduction is also observed in the "acidification" (16.77%) and "water use" (15.29%) impacts over the entire life cycle. These indicators follow the same pattern, showing a significant increase during the construction and renovation phases. However, once again, these increases are offset by a decrease in environmental impact during the usage phase.

Finally, the impacts of "photochemical ozone production," "aquatic ecotoxicity," "radioactive waste," "human toxicity," and "eutrophication" are respectively reduced by 9.42%, 9.61%, 8.94%, 7.26%, and 5.92%, with the construction and renovation phases negatively impacted and the usage phase positively impacted.

In conclusion, the installation of photovoltaic solar panels on two-thirds of the roof of Amphitheatre 1001 at the University of Yaoundé I presents a commendable environmental balance. Despite the negative impacts observed during the construction and renovation phases of the twelve (12) environmental impacts studied, the positive impacts from the usage phase more than compensate for them.

Green scenario: mixed mobility and solar PV scenarios

Just like in the case of the photovoltaic solar energy usage scenario, the electricity consumption and production are calculated after the dynamic thermal simulation. It shows that the amphitheatre consumes an average of 36,763 kWh of electricity for lighting each year. The photovoltaic solar panels, on the other hand, produce an average of 185,230 kWh annually. The detailed results of the life cycle analysis of the amphitheatre after applying this scenario are presented in Table 8.

It is observed that the combined use of the mobility scenario and photovoltaic solar energy usage has a very significant impact on the environmental performance of the amphitheatre. Eleven (11) out of twelve (12) indicators show a reduction of more than 10%.

The impacts with the highest reduction rates across the entire life cycle of the amphitheatre are "odour," "abiotic resource depletion," and "greenhouse effect," with reduction rates of 60.45%, 56.49%, and 45.57%, respectively. This is primarily due to a considerable reduction in impacts from transportation and electricity consumption during the building's usage phase.

The rate of reduction of the various environmental impacts of the amphitheatre over its entire life cycle is detailed in Fig. 8.

It is evident that the combined use of the mobility scenario and photovoltaic solar energy significantly impacts the environmental performance of the amphitheatre. Eleven (11) out of twelve (12) indicators show a reduction of more than 10%. The impacts with the highest reduction rates over the

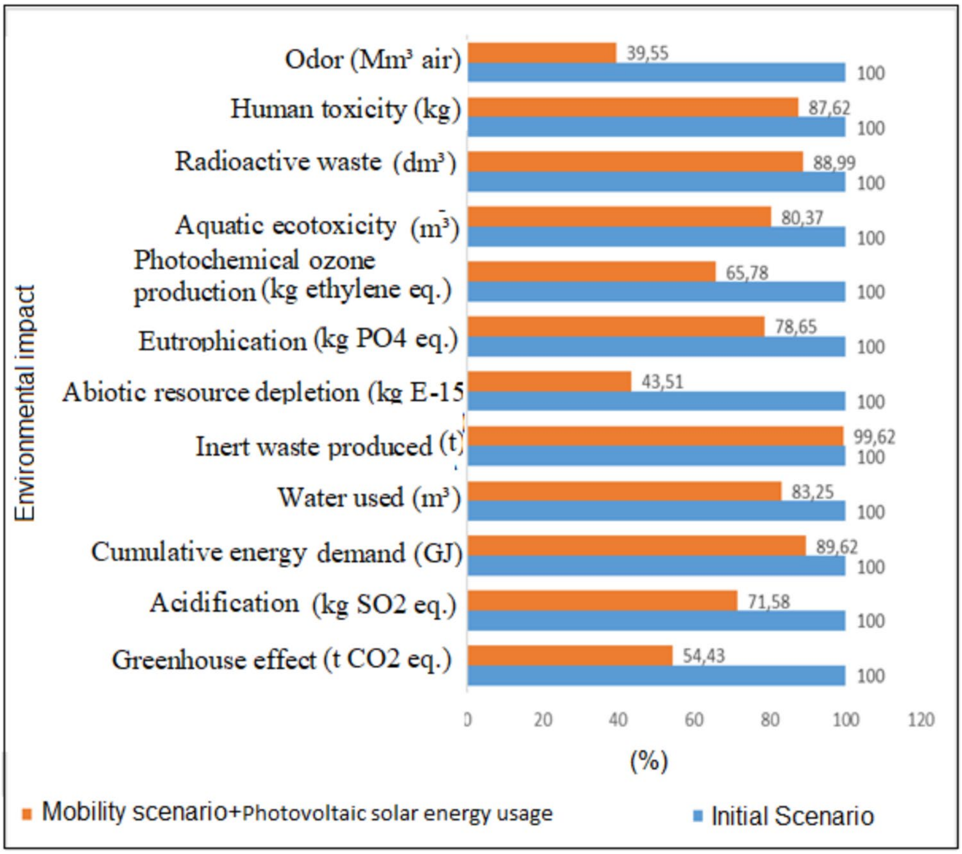


Fig. 8 Comparative diagram of environmental impacts for the "initial" and "mobility+photovoltaic solar energy usage" scenarios (functional unit: number of occupants)

Table 9 Variation of the LCA results of Amphitheatre 1001 at the University of Yaoundé I based on the rainwater use scenario

Impact	Initial scenario	Rainwater use scenario	Difference (%)
Greenhouse effect (t CO2 eq.)	12,545.19	12,542.09	0.02
Acidification (kg SO2 eq.)	167,345.97	167,316.81	0.02
Cumulative energy demand (GJ)	1,173,422.16	1,173,248.44	0.01
Water used (m^3)	1,150,121.94	1,115,354.04	3.02
Inert waste produced (t)	228,151.50	228,150.21	0.00
Abiotic resource depletion (kg E-15)	13	13.01	– 0.23
Eutrophication (kg PO4 eq.)	16,398.69	16,397.32	0.01
Photochemical ozone production (kg ethylene eq.)	82,934.54	82,929.08	0.01
Aquatic ecotoxicity (m^3)	775,724,298.05	775,558,109.68	0.02
Radioactive waste (dm^3)	1,545.27	1,544.71	0.04
Human toxicity (kg)	604,500.87	604,469.15	0.01
Odour (Mm^3 air)	39,619.37	39,677.86	– 0.15

entire life cycle of the amphitheatre are "odour," "abiotic resource depletion," and "greenhouse effect," with reduction rates of 60.45%, 56.49%, and 45.57%, respectively. This is primarily due to a considerable reduction in impacts related to transport and electricity use during the building's operation phase. Additionally, there is a much larger reduction in the impacts of "acidification" (28.42%) and "water use" (16.75%) across the life cycle. Finally, the impacts related to "photochemical ozone production," "aquatic ecotoxicity," "radioactive waste," "human toxicity," "cumulative energy demand," and "eutrophication" are reduced by 34.22%, 19.63%, 11.01%, 12.38%, and 21.35%, respectively. Overall, the simultaneous use of the mobility scenario and

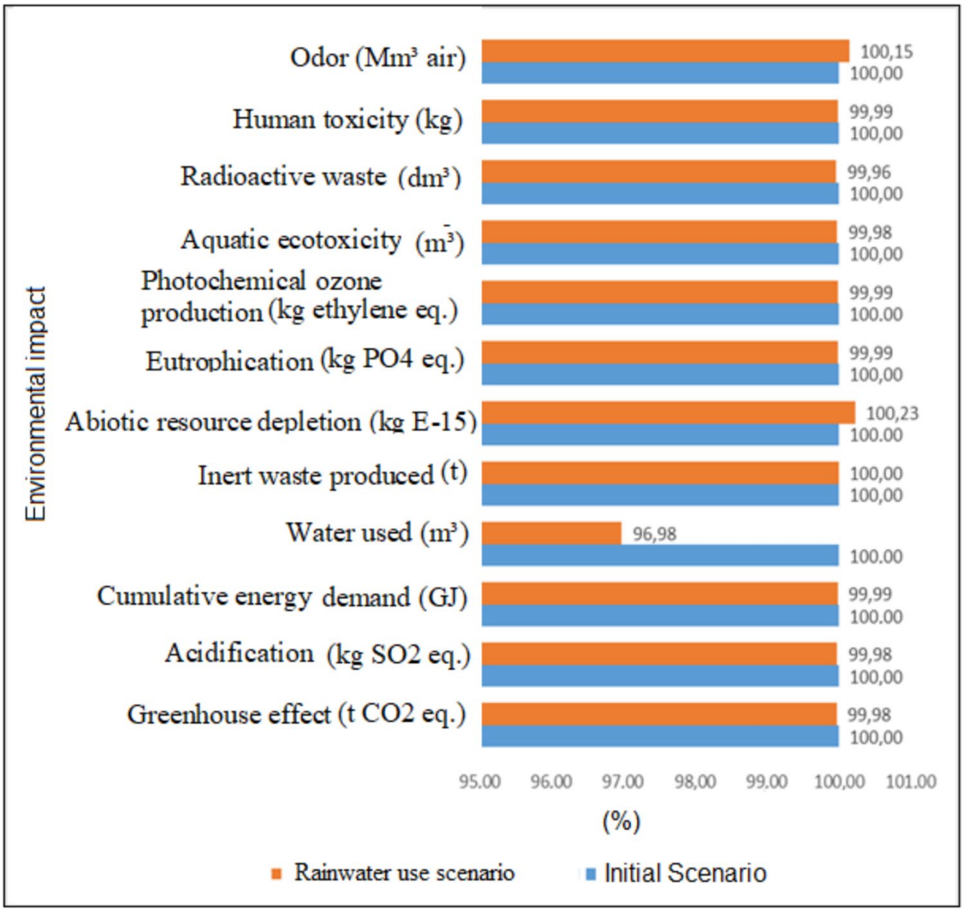


Fig. 9 Comparative diagram of the environmental impacts of the "initial" and "rainwater use" scenarios (functional unit: number of occupants)

the installation of photovoltaic solar panels on the amphitheatre results in a highly positive environmental balance and thus appears as an effective means of combating climate change, with a reduction of 45.57% in greenhouse gas emissions.

Rainwater use scenario

The reduction rate of the various environmental impacts of the amphitheatre over its entire life cycle is detailed in Table 9 and Fig. 9.

It is observed that the use of rainwater has a very minimal impact on the environmental balance of the amphitheatre. On average, the impacts are reduced by 0.23%. This corresponds to the amount of water and domestic hot water used during the operational phase.

Orientation scenario

The results of the dynamic thermal simulation of Amphitheatre 1001 after applying the four (04) orientation scenarios (45°, 90°, 135°, and 180°) are identical to those of the initial scenario. Indeed, after applying these four (04) scenarios, the heating/cooling needs of Amphitheatre 1001 remain zero, just as in the initial scenario. This is due to the fact that no heating or air conditioning temperature control system is applied to the building. However, orientation does impact a building's heating and cooling requirements. Given that there is no temperature control scenario in place, these needs remain null regardless of the building's orientation.

The results of the life cycle analysis (LCA) of the amphitheatre after applying these four (04) orientation scenarios are also identical to those of the initial scenario. This is because, aside from the building's orientation, no LCA calculation parameters were modified, and the amphitheatre's energy consumption after applying these orientation scenarios remains the same as in the initial scenario.

Comparison of different scenarios

To compare and determine the most environmentally friendly design parameters for the amphitheatre, the results

Table 10 Variations in environmental indicators across all studied scenarios compared to the initial scenario (functional unit: occupant)

Impact	Initial scenario	Mobility scenario	Solar photovoltaic energy use scenario	Mobility+Solar photovoltaic energy use scenario	Rainwater use scenario	Orientation scenario
Greenhouse effect (t CO2 eq.)	100.00	81.25	73.18	54.43	99.98	100.00
Acidification (kg SO2 eq.)	100.00	88.35	83.23	71.58	99.98	100.00
Cumulative energy demand (GJ)	100.00	96.72	92.90	89.62	99.99	100.00
Water use (m^3)	100.00	98.54	84.71	83.25	96.98	100.00
Inert waste produced (t)	100.00	99.72	99.90	99.62	100.00	100.00
Abiotic resource depletion (kg E-15)	100.00	100.00	43.51	43.51	100.23	100.00
Eutrophication (kg PO4 eq.)	100.00	84.57	94.08	78.65	99.99	100.00
Photochemical ozone production (kg ethylene eq.)	100.00	75.19	90.58	65.78	99.99	100.00
Aquatic Ecotoxicity (m^3)	100.00	89.98	90.39	80.37	99.98	100.00
Radioactive waste (dm^3)	100.00	97.93	91.06	88.99	99.96	100.00
Human toxicity (kg)	100.00	94.87	92.74	87.62	99.99	100.00
Odour (Mm^3 air)	100.00	92.72	46.83	39.55	100.15	100.00

from the various studied scenarios are compiled in Table 10 and Fig. 10.

To classify the different scenarios and prioritize the design parameters, the average reduction rates of the various studied scenarios are calculated.

Here are the design strategies ranked based on their impact on the environmental performance of the Amphitheatre 1001 at the University of Yaoundé I:

Mobility+Use of Photovoltaic Solar Panels: 26.42% average cumulative reduction across all indicators; Use of Photovoltaic Solar Panels: 18.07% average cumulative reduction across all indicators; Mobility: 8.35% average cumulative reduction across all indicators; Rainwater Recovery: 0.23% average cumulative reduction across all indicators; Orientation: 0.00% average cumulative reduction across all indicators.

After analysing Fig. 10, the following conclusions can be drawn:

Firstly, the combined management of mobility and the use of photovoltaic solar energy emerges as the most impactful scenario. Indeed, this scenario leads to significant reductions in environmental impacts across several categories: a reduction in odour emissions (60.45%), abiotic resource depletion (56.49%), greenhouse gas emissions (45.57%), photochemical ozone formation (34.22%), acidification (28.42%), eutrophication (21.35%), aquatic ecotoxicity (19.63%), water use (16.75%), human toxicity (12.38%), radioactive waste (11.01%), cumulative energy demand (10.38%), and inert waste production (0.38%).

Limiting car usage in favour of bicycles and walking for 80% of students, while installing photovoltaic solar panels on two-thirds of the roof of Lecture Hall 1001, would reduce the greenhouse gas emissions by nearly half throughout the entire lifecycle of the building.

In second place is the use of photovoltaic solar energy, which proves to be highly beneficial. Installing photovoltaic panels for electricity generation would allow the building to produce and consume its own electricity, with a surplus sufficient to power four other similarly configured lecture halls. Furthermore, this clean energy would significantly reduce environmental impacts, particularly those related to abiotic resource depletion (56.49%), odour emissions (53.17%), greenhouse gases (26.82%), acidification (16.77%), water use (15.29%), aquatic ecotoxicity (9.61%), photochemical ozone production (9.42%), radioactive waste (8.94%), human toxicity (7.26%), cumulative energy demand (7.10%), eutrophication (5.92%), and inert waste production (0.10%).

The use of photovoltaic solar energy should be a priority when considering ecological issues in the city of Yaoundé.

Mobility management ranks third. Limiting car usage in favour of bicycles and walking for 80% of students would significantly reduce impacts on photochemical ozone formation (24.81%), greenhouse gases (18.75%), eutrophication (15.43%), acidification (11.65%), aquatic ecotoxicity (10.02%), odour emissions (7.28%), human toxicity (5.13%), cumulative energy demand (3.28%), radioactive waste (2.07%), water use (1.46%), inert waste production (0.28%), and abiotic resource depletion (0%).

Mobility management should also be a priority in any ecological planning for the city of Yaoundé. The integration of rainwater harvesting systems in the lecture hall has a relatively low impact on the life cycle assessment (LCA) results of Lecture Hall 1001 at the University of Yaoundé I. Finally, the orientation of the lecture hall has no impact on its environmental performance.

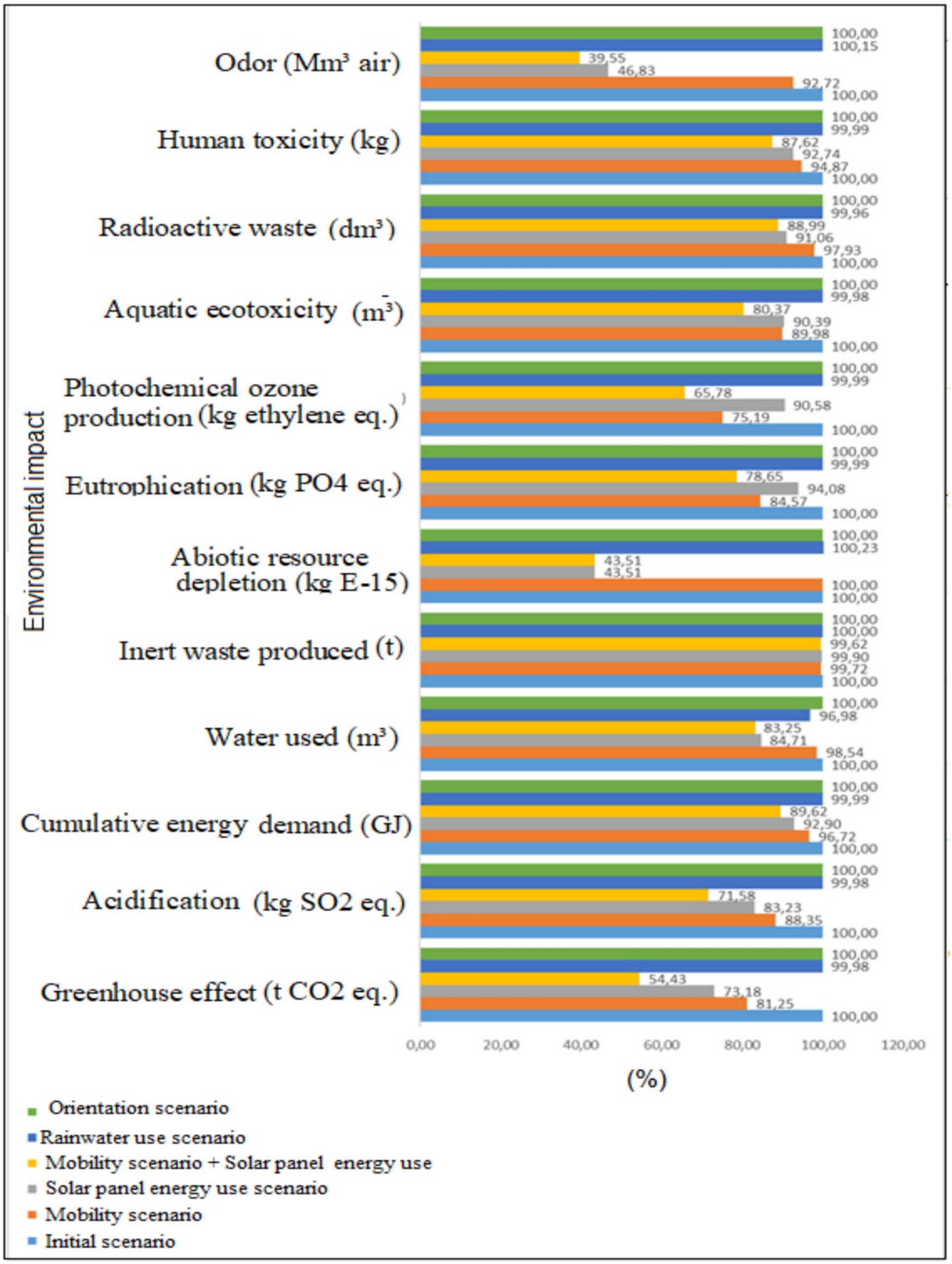


Fig. 10 Comparative diagram of the environmental impacts of all the studied scenarios (functional unit: number of occupants)

This section aims to present the results from the various simulations and their interpretations. Several scenarios were simulated, including mobility management, the use of photovoltaic solar energy, the simultaneous use of photovoltaic solar energy and mobility, rainwater management, and building orientation. The results obtained are particularly noteworthy, especially when compared to those reported in the literature, particularly in reference (Peuportier et al.2006). In the next section of this work, a general conclusion will be formulated, considering the overall study conducted and the perspectives that emerge from it.

Discussions

The results of this study provide a comprehensive understanding of the environmental performance of Amphitheatre 1001 across 12 impact categories and under multiple improvement scenarios. The findings confirm a dominant trend already highlighted in LCA literature: the operational phase overwhelmingly governs the life cycle impacts of educational buildings, especially in tropical regions where heating demand is naturally low. In this study, the operational phase contributes 94.54% of total environmental impacts, aligning with results from previous research on university buildings in warm climates, where operational impacts typically exceed 85–95% of the total footprint (ADEME 2014; Cabeza et al. 2014; Stephan et al. 2013; Ramesh et al. 2010).

Climate warming, passive thermal comfort, and future implications for building operation

While the present study assumes a naturally ventilated building without mechanical heating or cooling systems, it is important to situate these results within the broader context of rising ambient temperatures driven by climate change. In tropical regions such as Central Africa, projected increases in mean outdoor temperatures, higher frequency of heat waves, and elevated night-time temperatures may progressively challenge the effectiveness of passive thermal comfort strategies currently in use. For high-occupancy educational buildings like Amphitheatre 1001, increased internal heat gains combined with warmer outdoor conditions could reduce occupants' thermal comfort during peak periods, particularly in densely occupied lecture sessions. In such a context, two contrasting adaptation pathways may emerge. On one hand, there is a risk that declining thermal comfort could trigger the future installation of mechanical cooling systems (e.g., split-unit air conditioning), which substantially increase operational energy demand and greenhouse would gas emissions, thereby altering the life-cycle impact profile observed in this study. On the other hand, this pressure could instead accelerate the adoption of enhanced passive and low-energy design strategies, including improved natural ventilation control, solar shading, high-albedo or vegetated roofs, thermal mass optimization, ceiling fans, and adaptive occupancy scheduling. Previous studies in warm climates suggest that combining such passive measures can maintain acceptable comfort levels under moderate temperature increases while avoiding the carbon lock-in associated with HVAC deployment. From an LCA perspective, the latter pathway is particularly critical. The current dominance of the operational phase (94.54% of total impacts) indicates that any future shift toward active cooling would disproportionately amplify life-cycle environmental burdens. Consequently, climate-resilient design and operational strategies that preserve passive comfort should be considered a priority for tropical university campuses. Integrating climate adaptation thinking into early design and retrofit decisions is therefore essential to ensure that buildings like Amphitheatre 1001 remain low-carbon over their full service life, even under evolving climatic conditions.

Dominance of the operational phase and waste-related impacts

A notable and original finding is the exceptionally high contribution of waste generation (34.39%) within the operational phase. Unlike conventional LCAs in temperate regions, where electricity consumption and HVAC dominate buildings, in tropical African contexts often face waste management inefficiencies, leading to disproportionately high impacts on greenhouse gases and odours. Similar observations were reported in LCA studies of public buildings in Nigeria and Ghana, where waste-related emissions significantly exceeded modelled values in European benchmarks (Oyedele et al. 2017; Essandoh et al. 2020; Gervasio et al. 2014; Guinee et al. 2011; Stokes and Horvath 2006). The strong influence of transportation on GHG emissions (30.92%) is also consistent with evidence that, in urban African universities, commuter mobility can represent more than 25–40% of campus environmental impacts due to limited public transport infrastructure (Mbanaso 2020).

Mobility as a mitigation lever

The mobility scenario demonstrates substantial reductions across most environmental indicators, with notable declines in photochemical ozone formation (− 24.81%), GHG emissions (− 18.75%), and eutrophication (− 15.43%). These reductions are in line with previous studies showing that mode-shifting policies (cycling and walking) can reduce campus carbon emissions by 15–30%, depending on urban density and student commuting habits (Ünal et al. 2020, Azzali 2021). The sharp decline in photochemical ozone formation is logically tied to reduced NOx emissions from fuel combustion—already documented as a key driver of urban smog in tropical cities with high solar irradiance (Monks et al. 2009).

Photovoltaic integration: strong environmental benefits

The integration of photovoltaic (PV) systems shows some of the most substantial improvements, particularly for abiotic resource depletion (− 56.49%), odour emissions (− 53.17%), and greenhouse gas emissions (− 26.82%). These findings are consistent with global assessments showing that PV systems drastically reduce non-renewable resource use and improve air quality when replacing fossil-based grid electricity (Peng et al. 2014; Fthenakis and Kim 2010; Bhandari et al. 2015). Studies in Cameroon and West Africa also indicate similar reductions when buildings transition to solar energy, especially when the baseline grid electricity includes high shares of diesel generation (Nfah and Ngundam 2010).

Interestingly, your results highlight a temporary negative effect during the construction and renovation phases, due to PV manufacturing and transportation. This aligns with findings in LCA meta-analyses showing that while PV systems introduce initial environmental burdens, these are typically offset within 1–3 years of operation in tropical latitudes with high solar irradiance (Fthenafis and Kim 2010).

Synergy of mobility + solar energy

The combined scenario yields the strongest performance, reducing GHG emissions by 45.57%, odour emissions by 60.45%, and abiotic resource depletion by 56.49%. This synergy between supply-side mitigation (renewable energy) and demand-side mitigation (reduced mobility emissions) mirrors results from integrated climate strategies in sustainable campus models (Cabeza et al. 2014; Lozano et al. 2006). Several international studies emphasize that combining behavioural interventions with technological upgrades yields multiplicative—not simply additive—environmental benefits, especially in urban campuses with high occupancy rates (Ramesh et al. 2010; Brown et al. 2010; Nematchoua et al. 2020; Entreprise Coloniales 2024).

Minor impact of rainwater harvesting and orientation

Rainwater harvesting results in very low improvements (0.23%), reflecting similar findings from LCA research showing limited influence of water management features in buildings where potable water consumption is low relative to other operational impacts (Stokes and Horvath 2006). The absence of variation across orientation scenarios is expected, given that the building operates without heating or cooling systems. Prior work confirms that building orientation primarily matters when thermal loads are influenced by mechanical HVAC systems (Tuhus and Krarti, 2001). In naturally ventilated tropical buildings, orientation often has minimal effect on energy use—an observation fully supported by your model outputs.

Comparison of scenarios and implications for tropical university campuses

The comparative assessment of the investigated scenarios clearly indicates that mobility policies and on-site renewable energy deployment represent the most effective levers for reducing life-cycle environmental impacts in high-occupancy academic buildings located in tropical climates. These findings are consistent with large-scale campus and urban studies conducted in Kenya, South Africa, and Brazil, which similarly identified transportation patterns and electricity supply as dominant contributors to greenhouse gas emissions and primary targets for mitigation strategies (Essandoh et al. 2020; Ünal et al. 2020; Mattoni et al. 2020). By focusing on a Central African university campus, this study provides original empirical evidence from a region where building-scale life cycle assessments remain limited, thereby addressing an important research gap.

The results further demonstrate that campus-level interventions alone can achieve reductions exceeding 45% in life-cycle environmental impacts, a performance level comparable to comprehensive net-zero or low-emission strategies reported in European and Asian contexts. This highlights the strong mitigation potential of targeted operational and infrastructural measures, even in the absence of extensive technological retrofitting.

Beyond their environmental benefits, mobility-oriented strategies and renewable energy integration have also been shown to be economically viable pathways toward nearly zero-energy buildings (nZEB). Life cycle–based analyses have demonstrated that combined energy-efficiency and renewable scenarios can simultaneously reduce environmental burdens and total life cycle costs, particularly when long-term operational savings compensate for higher upfront investments (Nematchoua et al. 2021, 2022). In this regard, the present findings reinforce the relevance of campus-scale interventions as cost-effective and scalable solutions, supporting the transition toward nZEB concepts in tropical regions and resource-constrained academic environments.

Long-term evolution of building use and mobility patterns

Over the long term, both amphitheatre use and student transportation patterns are expected to evolve due to technological advances, urban development, and policy-driven decarbonisation strategies. While digital and hybrid teaching models may reduce peak occupancy in some contexts, large in-person lectures are likely to remain predominant in many developing-country universities, justifying the conservative assumption of sustained high occupancy adopted in this study. Similarly, future mobility trends—such as improved public transport, increased active mobility, campus densification, and the gradual electrification of vehicles—are expected to reduce the carbon intensity of commuting. The mobility scenarios explored in this work therefore, represent plausible future trajectories aligned with sustainable urban planning objectives, reinforcing the robustness of mobility and renewable energy strategies as key long-term mitigation levers for tropical university campuses.

Limitations of the study

Although this study provides a comprehensive Life Cycle Assessment of Amphitheatre 1001 and evaluates several mitigation scenarios, certain limitations must be acknowledged. First, the analysis relies on generic datasets from Ecoinvent 3.11 and default parameters within the PLEIADES software, which may not fully reflect local industrial processes and material production conditions in Cameroon. Second, the study assumes constant occupancy patterns, material service lives, and mobility behaviours over an 80-year period, whereas these factors may vary significantly over time due to demographic, behavioural, or policy changes. Third, dynamic thermal simulations were conducted without HVAC systems, which limits the assessment of orientation impacts and may underestimate the building's future energy needs under climate change. Additionally, the photovoltaic scenario uses idealised performance conditions, without considering real-world issues such as panel degradation, shading, or maintenance constraints. This study adopts a deterministic, scenario-based LCA approach and does not incorporate probabilistic or stochastic uncertainty analyses; therefore, potential variability in future climate conditions and material performance may influence the robustness of long-term environmental impact estimates. Another limitation of this study is the reliance on generic life cycle inventory datasets (e.g., Ecoinvent) due to the absence of Cameroon-specific environmental inventories for construction materials. Although local assumptions regarding transportation distances and electricity mix were incorporated where possible, the development of country-specific LCA databases would further improve the accuracy of future assessments. Finally, the LCA does not include economic costs, social impacts, or uncertainty analysis, which would strengthen decision-making for sustainable building design. Future research should integrate localised inventories, climate-resilient demand modelling, probabilistic uncertainty assessment, and multi-criteria sustainability evaluations.

Conclusion

This study conducted a comprehensive Life Cycle Assessment (LCA) of Amphitheatre 1001 at the University of Yaoundé I, assessing its environmental performance across the full life cycle and evaluating several mitigation scenarios. The results reveal that the combined scenario—integrating mobility management and photovoltaic (PV) solar energy—offers the highest environmental benefit, achieving reductions of 45.57% in greenhouse gas emissions, 56.49% in abiotic resource depletion, and 60.45% in odour emissions, among others. Individually, both PV installation and mobility improvements also demonstrated substantial impact mitigation, whereas rainwater harvesting and orientation changes produced marginal improvements, confirming that energy- and transport-related factors overwhelmingly shape the building's environmental profile. The findings hold significant implications for sustainable campus planning in tropical, fast-growing regions. For the University of Yaoundé, I, transitioning toward solar-powered infrastructure, represents a highly effective and technically feasible pathway toward reducing operational emissions while enhancing resilience to grid instability. Given that the PV system could supply electricity for up to four similar amphitheatres, decision-makers should consider prioritising large-roof public buildings for solar deployment. Likewise, reducing car dependency on campus—even partially—could substantially decrease pollution, improve air quality, and reduce traffic congestion in the university district. Therefore, policy measures such as building shaded pedestrian pathways, expanding bicycle infrastructure, and restricting vehicle access during peak academic hours are strongly recommended.

Beyond this study, future work should incorporate an economic feasibility assessment, particularly a cost–benefit analysis comparing the most effective scenarios (PV installation, mobility shifts, or their combination). Integrating financial indicators such as payback periods, maintenance costs, and carbon pricing would allow stakeholders to quantify both environmental and economic gains. Moreover, applying the LCA framework to other buildings on campus, especially those constructed with alternative materials and in varying climatic micro-conditions, would support the development of a standardised environmental design strategy for educational buildings in sub-Saharan Africa. Ultimately, such expanded analyses could guide policymakers toward a regional roadmap for achieving net-zero energy and emissions goals in the built environment.

Acknowledgements The authors would like to express their sincere gratitude to the University of Yaoundé I for providing access to the case study building and relevant data used in this research. The authors are grateful to colleagues and collaborators who provided valuable insights and technical support during the modelling and analysis phases, particularly in the use of the PLEIADES simulation and LCA tools. Finally, we would like to thank all anonymous reviewers for their constructive comments, which helped improve the quality and clarity of this manuscript.

Author contributions M.K. Nematchoua: Conceptualization, methodology, software, formal analysis, writing—original draft; J.A. Orosa: Supervision, review and editing, validation;R.M. Sendrahasina: Investigation, resources, data curation; V.K. Laura: Visualization, project administration, data collection; T.T. Eric: Software support, technical validation.S. Reiter: Review and editing, supervision, funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding This research received no external funding.

Data availability The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethics approval Not applicable.

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