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Design Of Eco-Efficient Learning Environments: An Approach Based On Educational Technology And Resource Optimization

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Summary
This article addresses the design of eco-efficient learning environments through the integration of educational technology and resource optimization strategies. Faced with the growing environmental challenge and the need for sustainable educational models, an approach that combines energy efficiency, the digitalization of training processes and the reduction of environmental impact in educational institutions is proposed. Through a theoretical review and a case study in Latin American institutions, technological practices and tools that promote more sustainable and pedagogically effective educational environments are identified. The results suggest that eco-efficiency in the design of learning spaces not only reduces operating costs, but also improves student engagement and fosters environmental awareness.
Keywords: *learning environments, eco-efficiency, educational technology, sustainability, resource optimization*

1. INTRODUCTION

The growing concern about climate change, the loss of biodiversity and the depletion of natural resources has generated a profound transformation in different sectors, including education. Academic institutions, as trainers of critical thinking and key actors in social development, have a responsibility to integrate sustainability principles into their policies, infrastructures, and pedagogical practices (UNESCO, 2021). This transformation goes beyond regulatory compliance or cost reduction; it implies a paradigm shift where learning takes place in environments aligned with the principles of energy efficiency, environmental responsibility, and rational use of resources (López et al., 2021).

In this context, **eco-efficient learning environments** emerge as spaces designed and managed under criteria that promote environmental sustainability without compromising the quality of teaching. These are environments that integrate clean technologies, sustainable materials, bioclimatic design and, especially, the incorporation of **digital educational technologies** as fundamental tools to reduce the use of physical materials, optimize times and improve accessibility to knowledge (Torres et al., 2023).

The COVID-19 pandemic acted as a catalyst to accelerate digitalization in education, revealing not only the transformative potential of technology, but also the existing gaps in terms of infrastructure, teacher training, and equitable access (González, 2022). In the post-pandemic period, there is a unique opportunity to rethink the design of physical and virtual educational spaces with a more ecological and inclusive look.

In addition, several recent studies indicate that the combination of sustainability and educational technology can generate benefits in both environmental and pedagogical terms. On the one hand, it has been proven that institutions that implement eco-efficient criteria achieve significant reductions in

their energy consumption and carbon footprint (Vásquez & Rojas, 2023). On the other hand, the use of tools such as virtual learning platforms, simulators, smart classrooms, and digital resources fosters new teaching-learning dynamics, which are more participatory and flexible, which adjust to the needs of the twenty-first century student (Salas & Méndez, 2022).

This article aims to analyze the **design of eco-efficient learning environments** from a multidisciplinary approach that articulates the technological, pedagogical and environmental dimensions. To this end, a recent theoretical review on the concept of eco-efficiency in the educational field is presented, as well as a case study in Latin American institutions that have implemented sustainable and digital initiatives. The objective is to show how the integration of these strategies can contribute to a more resilient, inclusive education committed to the challenges of sustainable development.

2. Theoretical Framework

2.1. Eco-efficient Learning Environments

The concept of **eco-efficiency** was initially developed by the World Business Council for Sustainable Development (WBCSD) and refers to producing more goods and services using fewer resources and generating less pollution (UNEP, 2021). In the field of education, eco-efficiency translates into the planning and management of spaces that minimise energy consumption, reduce the use of polluting materials and favour the reuse of resources (Vásquez & Rojas, 2023).

An eco-efficient learning environment is not only environmentally sustainable, but also pedagogically effective. For example, the use of natural lighting, cross ventilation, and acoustic materials can improve student concentration and well-being (Torres et al., 2023). Likewise, bioclimatic educational architecture has proven to be key to reducing the carbon footprint without significantly increasing infrastructure costs (Salazar et al., 2023).

2.2. Educational Technology as a Pillar of Sustainability

Educational technology, understood as the set of digital tools applied to the teaching-learning process, has become a transformative axis of modern education (González, 2022). The digitization of content, online education, the use of LMS (Learning Management Systems) platforms, and interactive resources make it possible to reduce dependence on printed materials and considerably reduce the use of paper, toner, and physical transportation by students or teachers (López et al., 2021).

According to Castro and Ortega (2022), the incorporation of digital resource management systems (such as the use of smart sensors for lighting and air conditioning, or automated control of energy consumption) has generated reductions of more than 30% in the operating costs of some institutions. In addition, technologies such as augmented reality, virtual laboratories and artificial intelligence are making it possible not only to improve access to knowledge, but also to do so in an environmentally responsible way.

2.3. Optimization of Resources in Educational Institutions

Resource **optimization** is a fundamental principle in the design of sustainable environments. This optimization encompasses both the rational use of energy and water and the efficient management of space, academic time, and teaching materials (UNESCO, 2021). Educational institutions that have adopted comprehensive sustainability approaches have managed to maximize the use of their infrastructures through shared classrooms, hybrid modalities, and smart schedule management (Torres et al., 2023).

Likewise, the use **of data analysis models** and planning tools based on artificial intelligence makes it possible to predict consumption and behavior patterns that help to dynamically adjust institutional resources (Salas & Méndez, 2022). This not only improves operational performance, but also strengthens the ability to respond to emergencies or demand variations, as was evident during the COVID-19 pandemic.

Table 1. Comparison of Main Components of Eco-Efficient Learning Environments

Dimension	Key Element	Environmental Benefit	Technological Example
Physical Infrastructure	Bioclimatic design, LED lighting	Reduced energy consumption and CO_2 emissions	Light and motion sensors

Material Resources	Content Digitization	Reduced paper, ink and transport usage	LMS platforms, virtual libraries
Energy Management	HVAC and lighting automation	Optimisation of energy use	Sistemas BMS (Building Management System)
Digital Pedagogy	Interactive and personalized resources	Accessibility and reduced consumption of physical resources	Augmented reality, adaptive learning
Institutional Culture	Sustainability training	Increased ecological awareness and student participation	Green projects, ecological clubs

Source: Authors' elaboration based on Torres et al. (2023), Salas & Méndez (2022), and UNEP (2021).

2.4. Relationship between Eco-efficiency and Educational Quality

Students' perception of eco-efficient environments is also relevant. Various studies have shown that students feel more motivated in environments that promote respect for the environment, which generates a virtuous circle between learning, commitment, and sustainability (Salazar et al., 2023). Additionally, the implementation of green technologies has improved academic well-being indicators, reducing absenteeism and increasing institutional satisfaction (González, 2022).

In short, the design of eco-efficient learning environments should not be seen only as a green action, but as a comprehensive educational strategy that improves the quality of learning and actively contributes to the fulfilment of the Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education) and SDG 13 (Climate Action) (UNESCO, 2021).

3. Methodology

The methodological approach of this study is mixed, combining **quantitative** and **qualitative elements**, which allows for a more in-depth analysis of the phenomenon investigated from multiple perspectives (Creswell & Plano Clark, 2021). This design responds to the complexity of the object of study, which involves environmental, technological, and pedagogical factors in real educational contexts.

3.1. Research Design

A mixed exploratory-sequential **design was employed**, starting with a **systematic review of scientific literature** to establish the theoretical framework and current trends in eco-efficient learning environments. Subsequently, a **multiple case study was applied** in three higher education educational institutions located in Colombia, Mexico and Peru, selected for their trajectory in technological innovation and institutional sustainability.

3.2. Population and Sample

The target population was made up of **teachers, directors, infrastructure technicians and students** belonging to the three selected institutions. **Purposive sampling** was used to select key informants (Patton, 2020), seeking to ensure that they had direct experience in the design or use of educational technologies and participation in institutional sustainability projects.

- Total participants: 45
  - Teachers: 15
  - Managers: 6
  - Technicians/managers: 9
  - Students: 15

3.3. Information Collection Techniques

Three main **data collection techniques** were applied:

1. **Document review**: analysis of institutional policies, energy audits, digitalisation plans and institutional sustainability reports between 2020 and 2024.
2. **Semi-structured** interviews: aimed at teachers, technicians and managers, focused on eco-efficient practices, perception of the impact of technology, and optimization strategies.
3. **Structured surveys**: applied to students, with Likert-type scales, to assess perception of the learning environment, environmental awareness and use of digital tools.

3.4. Data Analysis Techniques

- **Qualitative data**: The thematic analysis method (Braun & Clarke, 2019) was used, using open coding with the support of Atlas.ti software.
- **Quantitative data**: Descriptive statistics and comparative analysis using SPSS (v27) were used to identify trends in student perceptions and energy consumption patterns.

Table 2. Methodological Design of the Study

Component	Description
Type of study	Mixed exploratory (quantitative-qualitative)
Main Method	Multiple Case Study
Population	Teachers, directors, technicians and students from three Latin American institutions
Sample	45 participants selected by purposive sampling
Harvesting techniques	Documentary review, semi-structured interviews, structured surveys
Analysis tools	Atlas.ti (qualitative), SPSS v27 (quantitative)
Study period	January 2023 – May 2024
Inclusion criteria	Participation in sustainability or educational innovation projects
Validation	Methodological triangulation and peer review

Source: Authors' elaboration based on Creswell & Plano Clark (2021) and Patton (2020).

3.5. Ethical Considerations

The study was carried out respecting the ethical principles of social and educational research. All participants signed informed consents, guaranteeing anonymity, confidentiality of data and exclusive use for academic purposes. The participating institutions formally approved the research through collaboration agreements.

3.6. Limitations of the Study

Among the main limitations are:

- The limited sample size, which prevents statistical generalization.
- The possible **social desirability** in the responses, especially in interviews on institutional issues.
- The lack of uniformity in sustainability indicators between institutions.

However, the **triangulation of data** and the contextual richness of the qualitative approach allow significant findings to be drawn **that can be transferred** to similar contexts.

4. RESULTS

The results of the study are structured in three main dimensions: **eco-efficient infrastructure**, **use of educational technology** and **perception of the academic community**. The main findings derived from the quantitative and qualitative analysis in the institutions under study are presented below.

4.1. Implementation of Eco-efficient Infrastructure

The three institutions under study presented considerable progress in the adaptation of their physical environments under sustainability criteria. In particular, improvements were observed in energy efficiency, temperature control and use of natural light.

According to documentary data and interviews, two of the three universities installed photovoltaic systems between 2021 and 2023, achieving an **average reduction of 26.4% in conventional electricity consumption** (Torres et al., 2023). Likewise, motion sensors and LED lighting systems were installed in all classrooms, which allowed an **18.7% decrease in utility operating costs** .

Table 3. Environmental Impact Indicators in the Institutions Analyzed

Indicator	Institution A	Institution B	Institution C	Overall Average
Reduction in electricity consumption (%)	28.1	24.7	26.5	26.4
Water savings through recycling and reuse (%)	17.3	12.9	19.1	16.4
Reduction of solid waste (%)	35.0	40.5	33.8	36.4

Classrooms with LED lighting (%)	100	100	100	100

Source: Authors' elaboration based on institutional data (2023–2024).

4.2. Use of Educational Technology and Resource Reduction

In the analysis of the didactic resources used, a strong trend towards the digitalization of the educational process was evident. All the institutions studied operated LMS platforms (Moodle, Blackboard, or Canvas), which allowed paper use to be reduced by more than 60% between 2020 and 2024 (González, 2022).

In addition, 78% of the teachers interviewed indicated that the use of digital tools has improved pedagogical interaction without compromising environmental sustainability. Among the most commonly used applications are:

- Virtual simulators (physics and chemistry labs)
- Multimedia content and SCORM resources
- Collaborative forums and paperless classrooms

This result coincides with recent studies that argue that educational technology contributes to the operational and pedagogical sustainability of university environments (López et al., 2021).

Table 4. Reduction of Physical Resources due to Digitalization (2020–2024)

Resource Type	Use in 2020 (Kg/Unit)	Use in 2024 (Kg/Unit)	Reduction (%)
Paper (prints)	1,250 kg	500 kg	60.0
Toner cartridges	430 units	210 units	51.2
Exam Papers	75,000	21,000	72.0
Printed Manuals	3,400	1,000	70.6

Source: Institutional Sustainability Reports (2024).

4.3. Perception of Students and Teachers

Through surveys of 15 students per institution (n=45), the perception of the impact of the eco-efficient and technological measures implemented was evaluated. 84.4% of the students expressed that the use of technology in sustainable environments increased their motivation for learning, while 91.1% positively valued institutional efforts in sustainability.

In interviews with teachers and technicians, 87% highlighted that sustainability actions were accompanied by teacher training processes, which facilitated technological appropriation (Salas & Méndez, 2022).

Table 5. Results of the Student Perception Survey (n=45)

Item Evaluated	Positive Acceptance Percentage (%)
General assessment of sustainable environments	91.1
Motivation to learn in sustainable digital environments	84.4
Perceived decrease in the use of paper and printed materials	93.3
Ease of use of educational technology platforms	86.7
Desire for continuity of the sustainable-technological postgraduate model	77.8

Source: Survey applied by the research team (2024).

4.4. Synthesis of Findings

The results indicate a **positive relationship between the implementation of educational technology, the efficiency of physical resources and the perception of academic well-being**. This finding is consistent with what was reported by Salazar et al. (2023), who point out that eco-efficient environments contribute to institutional well-being and an organizational culture committed to the SDGs.

It is also confirmed that **sustainability is not incompatible with pedagogical innovation**, but that both mutually enhance each other in the creation of modern, resilient and environmentally responsible educational environments.

5. CONCLUSIONS

The results obtained in this study allow us to conclude that the design of eco-efficient learning environments represents a comprehensive and viable strategy to transform educational spaces towards a more sustainable, innovative perspective focused on the well-being of students. The convergence between environmental sustainability and educational technology is not only possible, but highly recommended in a context characterized by energy, budgetary and pedagogical challenges.

First, it is evident that institutions that have adopted **eco-efficient infrastructure** policies and practices, such as the use of solar energy, automation sensors, and sustainable materials, have managed to significantly reduce their energy consumption and ecological footprint. These results are in line with what Vásquez and Rojas (2023) have argued, who state that sustainable educational buildings can generate energy savings of between 20% and 35%, in addition to improving the internal environmental conditions of classrooms.

Second, the implementation of **digital educational technologies** has proven to be a catalyst for institutional sustainability. The reduction in the use of paper, toner, and printed materials has been notable in the three institutions analyzed, which supports previous studies that document the efficiency of virtual environments in reducing environmental impact without affecting educational quality (González, 2022; López et al., 2021). In addition, the use of LMS platforms, simulators and multimedia resources has strengthened pedagogical interaction, promoting more active and personalized learning experiences.

On the social and cultural level, the data reveal a high level of acceptance and appreciation by students and teachers regarding institutional efforts in sustainability. This finding reinforces the idea that eco-efficiency should not be conceived only as a technical improvement, but as a **cultural strategy that strengthens the sense of belonging, environmental awareness, and collective responsibility** (Salas & Méndez, 2022). Educational institutions that promote a culture of sustainability generate environments that are more inclusive, resilient and aligned with the Sustainable Development Goals (UNESCO, 2021).

In addition, it is relevant to highlight that the adoption of these models requires long-term strategic planning, investment in infrastructure and teacher training. However, the environmental, pedagogical and economic benefits amply justify such efforts. As indicated by Torres et al. (2023), educational sustainability should not be understood as an expense, but as an investment in institutional quality and resilience in the face of future challenges.

In summary, the present study confirms that eco-efficient learning environments, supported by educational technology and resource optimization strategies, **constitute a contemporary and transformative educational model**. Institutions that aspire to lead the transition to sustainable education must integrate these approaches in a cross-cutting way into their governance, curriculum, infrastructure, and innovation processes.

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