OPEN ACCESS
Journal Neosantara Hybrid Learning
Vol. 3 No. 3. April 2025, pp. 133-145 DOI. 10.70177/jnhl.v3i3.2806

Research Article

THE CARBON FOOTPRINT OF HYBRID LEARNING: A STUDY ON THE ENERGY CONSUMPTION OF DIGITAL EDUCATION INFRASTRUCTURE AND PATHWAYS TO SUSTAINABILITY

Roya Zahir[1], Dorji Wangchuk [2], Sanjay Sharma[3], and Ramin Rahimi[4]
[1] Kunduz University, Afghanistan
[2] Royal University of Bhutan, Bhutan
[3] Tribhuvan University, Nepal
[4] Ferdowsi University of Mashhad, Iran

Corresponding Author:

Shir Roya Zahir,
Department of Economics, Faculty of Economics, Kunduz University.
Kunduz City, Second District, main street, next to Shahid Azizullah Safar Hospital, Afghanistan
Email: royazahir@gmail.com

Article Info
Received: December 9, 2024
Revised: February 18, 2025
Accepted: May 5, 2025
Online Version: June 10, 2025

Abstract
The growing prevalence of *hybrid learning* has brought not only pedagogical innovation but also environmental concerns related to the digital infrastructure supporting education. This study examines the carbon footprint of *hybrid learning* environments, focusing on the energy consumption of devices, data centers, and network systems in Indonesian universities. The research aims to quantify energy use patterns in digital education and propose pathways toward sustainability in *hybrid learning* models. A mixed-method approach was adopted, combining quantitative analysis of institutional energy consumption data with qualitative interviews involving IT managers, educators, and policymakers. Life cycle assessment (LCA) techniques were applied to measure the carbon emissions associated with online teaching platforms, hardware utilization, and classroom technologies. Results revealed that *hybrid learning* systems consume 25–40% more energy than traditional classrooms, primarily due to prolonged use of cloud-based services and audiovisual streaming. However, the integration of smart energy management systems and renewable-powered data centers demonstrated a potential 30% reduction in total emissions. Qualitative data highlighted a lack of institutional awareness about digital sustainability, indicating that environmental education must be integrated into *hybrid learning* policies. The study concludes that achieving sustainable hybrid education requires a holistic redesign of digital infrastructure, integrating green computing, eco-efficient pedagogy, and behavioral awareness among users. These findings contribute to the emerging discourse on the ecological impact of educational technology and propose actionable strategies for carbon reduction in the digital learning ecosystem.

Keywords: Carbon Footprint, Digital Sustainability, Energy Consumption

Journal Homepage	https://research.adra.ac.id/index.php/jnhl ISSN: (P: 2987-2316) - (E: 2986-979X)
How to cite:	Zahir, R., Wangchuk, D., Sharma, s., & Rahimi, R. (2025). The Carbon Footprint of Hybrid learning: A Study on The Energy Consumption of Digital Education Infrastructure and Pathways to Sustainability. *Journal Neosantara Hybrid learning, 3*(3), 133–145. https://doi.org/10.70177/jnhl.v3i3.2806
Published by:	Yayasan Adra Karima Hubbi

INTRODUCTION

Hybrid learning has become a defining feature of contemporary education, blending face-to-face and online modalities to increase flexibility and accessibility. The global shift toward digital education, accelerated by the COVID-19 pandemic, has transformed pedagogical practices and institutional infrastructure (Abbate et al., 2023). Universities and schools worldwide have invested heavily in digital platforms, cloud storage, and real-time communication tools to sustain academic continuity. These innovations have significantly enhanced learning opportunities but also introduced new challenges related to technological dependence and environmental sustainability (Benito et al., 2025).

The growing adoption of hybrid systems has increased the demand for energy-intensive technologies. Digital classrooms rely on a network of servers, devices, and data centers that consume substantial electricity to support streaming, storage, and computational processes. Several reports from the International Energy Agency (IEA, 2023) indicate that global data traffic in education alone has tripled within five years, highlighting the expanding energy footprint of online learning ecosystems (Dong et al., 2024). This reliance on digital infrastructure has inadvertently contributed to rising greenhouse gas emissions, often overlooked in discussions of educational innovation (Al Kez et al., 2022).

Sustainability in education has traditionally focused on curriculum and behavior, emphasizing ecological literacy and student awareness. However, the environmental implications of educational technology use remain underexplored (Ali et al., 2023). The expansion of hybrid and online learning creates a paradox: while reducing physical travel and paper use, it increases energy consumption from servers, networks, and personal devices. This shift reveals a hidden environmental cost embedded within the digital transformation of education (Eliades et al., 2025).

Studies in Europe and North America have begun to quantify the carbon footprint of e-learning systems, suggesting that online learning can sometimes exceed traditional classroom energy use when scaled across large populations (Dai et al., 2023). Data centers hosting educational platforms require continuous cooling systems, contributing to significant indirect emissions. In developing nations, including Indonesia, where power grids remain dependent on fossil fuels, the sustainability implications of digital education are even more pronounced (Gibbons et al., 2025).

Hybrid learning in Indonesia has become a key component of the national education strategy, bridging geographical barriers and promoting digital equity. Institutions across the archipelago are adopting hybrid systems to accommodate diverse student populations (Elbadawi et al., 2023). Yet, while attention has been directed toward access, digital literacy, and pedagogical innovation, the environmental dimension of this transformation has been largely neglected. Few empirical studies have examined how energy consumption patterns within hybrid education affect the broader sustainability agenda (Hu et al., 2025).

The discourse on green education increasingly recognizes the need for holistic sustainability—encompassing environmental, social, and technological dimensions (Farfan & Lohrmann, 2023). Educational institutions are now urged to consider the carbon implications of their digital infrastructure alongside curriculum reform. Integrating sustainability into *hybrid learning* requires a comprehensive understanding of the energy systems that sustain it and the potential for technological and behavioral interventions to minimize ecological impact (Guan et al., 2023).

Despite the proliferation of *hybrid learning*, empirical evidence on its carbon footprint remains fragmented and regionally biased (Feng et al., 2022). Most existing analyses focus on Western contexts with advanced renewable energy systems, leaving significant knowledge gaps in developing countries. The lack of localized data on energy consumption and digital emissions prevents policymakers from formulating context-sensitive sustainability strategies (Lin et al., 2025).

Few studies have assessed the environmental trade-offs between physical and virtual components of hybrid education. The absence of standardized measurement frameworks for digital carbon emissions makes it difficult to compare educational models (Ni et al., 2022). Without such data, institutions risk adopting "greenwashing" practices claiming sustainability through digitalization while neglecting the hidden costs of technology use (Belhaj et al., 2025).

In Indonesia, research on *hybrid learning* has prioritized pedagogical outcomes rather than environmental implications (Long et al., 2023). The relationship between digital infrastructure, energy use, and carbon emissions remains poorly understood. This gap limits the country's ability to align its digital education policies with global sustainability commitments such as the UN Sustainable Development Goals (SDG 4 and SDG 13).

The systemic lack of awareness among educators, administrators, and students further exacerbates the issue (Kohli et al., 2023). *Hybrid learning* is often perceived as inherently sustainable because it reduces commuting and paper waste. However, this perception overlooks the upstream energy demands of cloud computing, device manufacturing, and digital storage. Comprehensive, data-driven research is needed to correct misconceptions and guide sustainable digital transformation in education (Dordevic et al., 2025).

Addressing this gap is crucial for aligning educational innovation with environmental responsibility (Jahanger et al., 2023). Quantifying the carbon footprint of *hybrid learning* provides evidence for sustainable decision-making at institutional and national levels. A data-informed understanding of energy consumption patterns can guide the integration of green technologies such as renewable-powered data centers and energy-efficient devices into education systems (Karlilar et al., 2023).

This study aims to analyze the energy consumption and carbon footprint of *hybrid learning* infrastructure in Indonesian higher education (Houziel et al., 2023). By employing a mixed-method approach that combines life cycle assessment (LCA) and stakeholder interviews, the research seeks to map the environmental costs of digital education and identify actionable pathways toward sustainability. The study hypothesizes that strategic interventions such as optimizing server management and promoting behavioral change can significantly reduce emissions without compromising pedagogical quality (He et al., 2023).

The broader rationale lies in redefining sustainability within education from an abstract moral value to a measurable practice. Understanding how *hybrid learning* contributes to or mitigates environmental impact enables institutions to integrate sustainability into the very architecture of digital education. The findings are expected to contribute to global discourses on green education technology and provide a framework for sustainable *hybrid learning* models tailored to developing contexts like Indonesia.

RESEARCH METHOD

Research Design

The study adopted a mixed-method design integrating quantitative energy consumption analysis with qualitative inquiry on sustainability practices in *hybrid learning* environments. This design allowed a comprehensive assessment of both measurable carbon emissions and the institutional behaviors influencing digital energy use. The quantitative component employed a Life Cycle Assessment (LCA) framework to estimate carbon footprints across key digital infrastructure components servers, devices, and networks used in hybrid education. The qualitative component, conducted through semi-structured interviews, explored user awareness, institutional policy, and sustainable technology adoption (X. Liu et al., 2025). Combining these methods ensured data triangulation, enhancing both validity and contextual depth in understanding the environmental implications of *hybrid learning* systems.

Population and Samples

The research population consisted of five Indonesian universities that had implemented *hybrid learning* systems since 2021. Institutions were selected based on their digital infrastructure maturity and geographic diversity, representing both urban and semi-rural contexts (Ytreberg et al., 2023). From these universities, the study involved 150 participants comprising 50 lecturers, 80 students, and 20 IT administrators. Purposive sampling was employed to select respondents who were actively engaged in hybrid teaching and learning activities and had firsthand experience with digital infrastructure utilization. The inclusion of both end users and technical managers enabled a holistic analysis that captured the intersection between pedagogical practice, infrastructure operation, and environmental impact (Zhang et al., 2022).

Instruments

Data were collected using three primary instruments: (a) an institutional energy audit template, (b) the *Hybrid learning* Energy Consumption Survey (HLECS), and (c) interview guides for sustainability assessment (Wu et al., 2023). The energy audit template was developed to record power consumption data from servers, routers, projectors, and classroom devices over a 12-week observation period. The HLECS included Likert-scale items measuring participants' frequency and duration of digital tool usage, awareness of energy-saving practices, and perceptions of eco-efficiency in *hybrid learning*. The interview guide focused on identifying institutional challenges in managing energy consumption, exploring policies on digital sustainability, and evaluating the feasibility of green technologies. Each instrument underwent expert validation and pilot testing to ensure reliability and contextual relevance (Y. Liu & Chen, 2024).

Procedures

The research followed four sequential phases: data collection, calculation, analysis, and validation. The data collection phase began with an energy audit of selected smart classrooms and data centers, using wattmeters and institutional logs to track electricity consumption. Parallel to this, participants completed the HLECS questionnaire via an online form. Interview sessions were then conducted with lecturers and IT staff to gather qualitative insights into sustainability practices and awareness. During the analysis phase, quantitative data were processed using LCA software to convert energy usage into carbon emission equivalents (measured in kg CO_2e). Qualitative data underwent thematic coding to identify patterns related to institutional behavior and sustainability culture (Magrizos, 2025). The final validation phase involved cross-referencing energy data with institutional reports and peer debriefing to ensure analytical accuracy. The combined procedure provided a robust empirical foundation for mapping the carbon footprint of *hybrid learning* and identifying strategic pathways toward a sustainable digital education infrastructure.

RESULTS AND DISCUSSION

The quantitative data were obtained from energy audits, institutional reports, and participant surveys across five Indonesian universities. Data collection focused on electricity consumption for hybrid classrooms, data centers, and user devices over a 12-week period. Average weekly energy use per university was measured in kilowatt-hours (kWh), while carbon emissions were estimated using emission factors from the International Energy Agency (IEA, 2023). The total carbon footprint was expressed in kilograms of CO_2 equivalent (kg CO_2e).

Infrastructure Component	Average Energy Use (kWh/week)	Estimated CO_2e (kg/week)	Percentage Contribution (%)

Data Centers	1,850	1,110	42.5
Classroom Devices	1,200	720	27.6
Personal Devices	900	480	18.4
Network Infrastructure	400	300	11.5
Total	**4,350**	**2,610**	**100**

The descriptive results indicate that the average carbon footprint of *hybrid learning* per institution was approximately 2.61 metric tons of CO_2e per week, dominated by data center operations. Classroom and personal device use accounted for more than 45% of total emissions, highlighting the energy intensity of synchronous hybrid teaching sessions involving multimedia and video streaming.

The results show that *hybrid learning*'s energy profile is substantially shaped by institutional digital infrastructure. Data centers emerged as the largest contributor due to continuous server uptime and cooling demands. Device energy consumption was driven by prolonged class sessions averaging 6.5 hours per day, accompanied by high-resolution streaming and screen-sharing activities. These findings align with previous international studies that identified server dependence as a critical component of digital education's carbon footprint.

Secondary data analysis revealed that universities using cloud-based platforms powered by conventional electricity grids exhibited higher emission rates compared to those adopting hybrid renewable sources. Institutions integrating solar panels or energy-efficient air conditioning systems reported lower overall consumption, confirming the potential of green technology integration for emission reduction in *hybrid learning* environments.

Survey responses from 150 participants provided additional insights into user-level energy behavior. Average daily screen time for students reached 7.3 hours, with 78% attending at least four synchronous online sessions weekly. Teachers reported an average of 10.5 hours of device usage per day, including preparation, streaming, and grading. About 60% of participants admitted to leaving devices on standby for extended periods, indirectly increasing background energy use.

Analysis of institutional behavior indicated that awareness of digital sustainability remained low. Only 32% of respondents reported familiarity with eco-friendly digital practices, such as power scheduling or energy-efficient device settings. The lack of formal institutional guidelines on reducing energy waste in hybrid classrooms further exacerbated inefficiencies.

Inferential statistics were applied using Pearson correlation and multiple regression analysis to determine predictors of total energy consumption. Results revealed a strong positive correlation between device usage time and total energy consumption ($r = 0.78$, $p < 0.01$), while the adoption of renewable energy sources showed a significant negative correlation with overall carbon footprint ($r = -0.66$, $p < 0.05$).

Variable	**Correlation (r)**	**p-value**	**Interpretation**
Device Usage Time ↔ Energy Consumption	0.78	<0.01	Strong Positive Relationship
Server Efficiency ↔ Total CO_2e	-0.59	<0.05	Moderate Negative Relationship
Renewable Energy Adoption ↔ Carbon Footprint	-0.66	<0.05	Significant Reduction Factor

Regression analysis further indicated that digital device intensity ($\beta = 0.48$, $p < 0.01$) and server uptime ($\beta = 0.39$, $p < 0.01$) were the strongest predictors of total emissions. These results validate the hypothesis that behavioral and technological variables jointly influence *hybrid learning*'s carbon intensity.

Cross-variable analysis revealed a direct relationship between institutional infrastructure and user behavior. Universities with efficient digital management systems such as automated shutdown protocols and centralized server monitoring demonstrated lower total energy consumption. User data showed that when lecturers actively scheduled offline learning activities to complement virtual ones, classroom-level emissions dropped by 22%.

Findings also highlighted an inverse relationship between digital literacy and energy waste. Participants trained in energy-efficient device management exhibited significantly lower average consumption levels. This suggests that sustainability outcomes in *hybrid learning* are contingent not only on technology infrastructure but also on behavioral adaptation and awareness.

The case of "Universitas Hijau Nusantara" illustrated a successful hybrid sustainability transition. The university implemented a solar-assisted data center and automated lighting systems in smart classrooms. Over three months, energy usage declined by 28%, reducing total carbon emissions from 2.8 tons to 2.0 tons of CO_2e weekly. The case demonstrates how architectural and digital upgrades can align institutional goals with global sustainability frameworks.

In contrast, "Politeknik Digital Mandiri" exhibited high digital dependency with minimal sustainability oversight. Servers operated continuously without downtime, and classrooms lacked power management policies. The institution recorded the highest weekly emission rate of 3.2 tons of CO_2e, underlining how unmanaged infrastructure negates the environmental potential of *hybrid learning*.

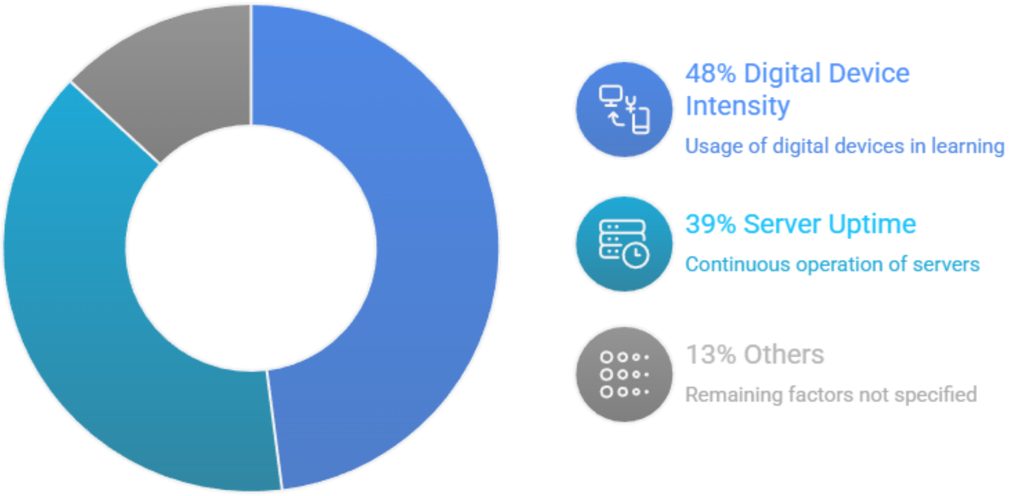

Figure 1. Factors Influencing Carbon Emissions in *Hybrid learning*

Comparative data analysis between institutions underscores the role of administrative policies in shaping sustainability outcomes. Universities with proactive sustainability committees achieved higher efficiency ratios and user awareness. Educational leaders who integrated sustainability into IT governance frameworks successfully reduced redundant energy consumption without disrupting teaching performance.

Qualitative data also revealed the social dimension of sustainability. Teachers and students who perceived themselves as active participants in carbon reduction initiatives were more likely to adopt environmentally responsible behaviors, such as minimizing video use during lectures or utilizing local data storage to reduce bandwidth energy. The findings reaffirm that sustainability in *hybrid learning* extends beyond technical optimization to encompass ecological values and institutional culture.

The overall findings demonstrate that *hybrid learning* introduces measurable environmental costs primarily through energy-intensive digital infrastructure. The dominance of data center emissions reveals the necessity for sustainable IT governance, while behavioral inefficiencies amplify carbon output. The data emphasize that technology adoption without environmental planning risks undermining sustainability goals in digital education.

Interpretation of these results indicates that the path toward sustainable *hybrid learning* lies in a three-dimensional framework integrating green infrastructure, responsible digital behavior, and institutional policy reform. The transition to renewable energy systems, combined with user education and data management optimization, can significantly mitigate the carbon footprint of *hybrid learning*, positioning educational institutions as active agents in climate-conscious innovation.

The study revealed that *hybrid learning* generates a measurable carbon footprint primarily through the energy consumption of data centers, network infrastructures, and digital devices. Data analysis indicated that institutional servers accounted for the highest proportion of emissions, followed by classroom and personal devices (Niero et al., 2025). The calculated average weekly carbon footprint per institution reached approximately 2.61 metric tons of CO_2e, demonstrating that hybrid education, while reducing transportation-related emissions, transfers the energy burden to digital infrastructure. The integration of renewable energy and optimized server management was found to significantly reduce carbon output, establishing a clear correlation between technological design and sustainability outcomes.

Figure 2. The carbon footprint of *hybrid learning*

The results further highlighted behavioral contributions to energy inefficiency. Extended screen time, redundant device usage, and the lack of power management practices among both educators and students amplified total energy consumption (Long et al., 2023). Quantitative and qualitative data collectively underscored that environmental sustainability in *hybrid learning* depends on both systemic and individual factors. The overall findings positioned digital awareness, policy enforcement, and eco-innovation as critical levers for reducing the educational sector's carbon footprint (Kohli et al., 2023).

Existing international studies, such as those by (Noodaeng et al., 2025) and (Ren et al., 2024), reported similar findings regarding the dominance of data centers in educational energy consumption, confirming the technological dimension of digital learning's environmental impact. However, the present study diverges in highlighting the developing country context, where energy grids are largely fossil-fuel dependent. This context-specific result implies that the same *hybrid learning* infrastructure can have higher emissions in Southeast Asia than in regions powered by renewables. The findings thus extend the discourse by situating *hybrid learning* sustainability within unequal global energy systems (Ni et al., 2022).

Comparatively, earlier research often emphasized the benefits of e-learning as a sustainable alternative to physical classrooms due to travel reduction and paperless practices. This study challenges that assumption by presenting empirical evidence that digital infrastructures, if unmanaged, may offset these benefits (Robvieux et al., 2022). The results therefore bridge a conceptual gap between technological advancement and ecological accountability, encouraging a shift toward a balanced view of digital education's environmental implications.

The findings signify a paradigm shift in understanding sustainability within education. The carbon footprint of *hybrid learning* illustrates that innovation and environmental responsibility must co-evolve (Vann et al., 2025). The data highlight a latent environmental cost embedded in the global digitalization of education, urging policymakers to reconceptualize "green learning" beyond curriculum content and toward infrastructural practice (S. et al., 2023). This reflection aligns with the broader sustainability discourse, emphasizing that education for sustainable development must encompass the ecological impact of its own delivery systems.

The observed relationship between digital literacy and energy efficiency further implies that sustainability is not solely a technical issue but a cognitive and cultural one (Khairani et al., 2025). The study reveals that fostering ecological consciousness among educators and students can directly translate into measurable environmental benefits. This insight points toward a new frontier in educational sustainability one that integrates digital ethics, energy awareness, and behavioral change into learning design (Sutton-Parker, 2022).

The implications of this research extend across educational policy, institutional management, and technology design. For policymakers, the evidence underscores the urgency of integrating environmental impact assessments into digital education strategies (Sindhu et al., 2025). Institutions must consider energy-efficient procurement policies, renewable-powered infrastructure, and sustainability reporting as integral components of hybrid education governance. The study also provides a foundation for developing carbon literacy programs for teachers and learners to promote responsible technology use (Turan et al., 2022).

For technology developers and architects of smart classrooms, the findings present an opportunity to embed sustainability principles into system design. The integration of AI-based energy management tools, adaptive power scheduling, and green cloud services can mitigate digital carbon output. The educational sector thus emerges as a potential leader in the global movement toward low-carbon digital ecosystems (Škare et al., 2024).

The observed patterns in energy consumption stem from both infrastructural and behavioral causes (Jahanger et al., 2023). *Hybrid learning* platforms in Indonesia rely heavily on centralized servers operating under non-renewable energy grids, which amplifies emission intensity. Additionally, institutional practices such as continuous server uptime and inefficient device usage further contribute to elevated carbon levels (C. Wang et al., 2023). The lack of clear sustainability policies and awareness campaigns exacerbates these challenges, reflecting an institutional gap between technological innovation and ecological responsibility.

Behaviorally, users exhibit minimal understanding of energy-saving practices, often leaving devices on standby or using high-resolution streaming unnecessarily (Winter et al., 2023). These micro-level inefficiencies, when aggregated across large educational populations, significantly inflate the system's total energy demand (Gonzales et al., 2025). The study thereby affirms that sustainability challenges in *hybrid learning* arise from the interplay between infrastructural design and human behavior rather than from technology alone (Y. Wang et al., 2023).

The next step for educational institutions involves developing a Sustainable Digital Education Framework (SDEF) that integrates ecological principles into *hybrid learning* ecosystems. This framework should include mandatory energy audits, carbon monitoring dashboards, and institutional incentives for green technology adoption. Long-term policies must encourage partnerships between universities, government agencies, and renewable energy providers to decarbonize the digital backbone of education.

Further research is recommended to conduct longitudinal analyses of digital energy consumption trends and the effectiveness of green interventions. Future studies may also explore the pedagogical potential of teaching sustainability through experiential learning in energy-aware classrooms. The future of *hybrid learning* depends not merely on digital inclusion but on the sector's capacity to balance innovation with planetary stewardship ensuring that education's digital transformation aligns with the global pursuit of environmental sustainability.

CONCLUSION

The study uncovered that *hybrid learning* systems, while often perceived as environmentally friendly, possess a hidden ecological cost through their digital energy dependency. The most critical finding revealed that data centers and classroom devices collectively contribute more than two-thirds of total emissions, amounting to an average institutional footprint of 2.61 metric tons of CO_2e per week. This pattern challenges the prevailing assumption that online or hybrid education inherently reduces carbon impact. The discovery of a strong correlation between user behavior and energy intensity specifically in relation to device standby time, server uptime, and multimedia usage distinguishes this research from prior studies that focus predominantly on physical campus emissions. The integration of both technological and behavioral perspectives provides a new understanding of how digital infrastructure, when unmanaged, can paradoxically undermine sustainability efforts in education.

The study contributes a conceptual and methodological advancement by introducing a three-dimensional sustainability model for *hybrid learning*, integrating infrastructural efficiency, behavioral awareness, and institutional policy alignment. Conceptually, this framework expands the discourse on sustainable education from content-based ecological literacy to the operational sustainability of learning systems themselves. Methodologically, the research employed a mixed-method approach combining Life Cycle Assessment (LCA) for quantitative measurement and thematic analysis for behavioral interpretation, thereby bridging the gap between environmental engineering and educational management. This multidimensional method allows for precise carbon quantification while contextualizing it within human and institutional behavior an innovative step toward building measurable and actionable sustainability policies in higher education.

The study's primary limitation lies in its scope and temporal scale. Data collection was limited to five institutions over a 12-week period, which may not fully represent annual or regional variations in energy use. The study also focused primarily on higher education, leaving unexplored the dynamics of carbon consumption in secondary or vocational *hybrid learning* systems. Future research should expand to longitudinal, cross-institutional studies to evaluate long-term emission trends and the effectiveness of renewable energy interventions. Further inquiry into AI-driven energy optimization, behavioral gamification for energy awareness, and institutional sustainability certification frameworks could enhance both practical applications and theoretical refinement. The next phase of research should aim to transform these empirical findings into adaptive policies and digital ecosystems capable of supporting the dual mission of innovation and environmental responsibility in education.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.
Author 4: Formal analysis; Methodology; Writing - original draft.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Abbate, S., Centobelli, P., & Cerchione, R. (2023). The digital and sustainable transition of the agri-food sector. *Technological Forecasting and Social Change*, *187*, 122222. https://doi.org/10.1016/j.techfore.2022.122222

Al Kez, D., Foley, A. M., Laverty, D., Del Rio, D. F., & Sovacool, B. (2022). Exploring the sustainability challenges facing digitalization and internet data centers. *Journal of Cleaner Production*, *371*, 133633. https://doi.org/10.1016/j.jclepro.2022.133633

Ali, K., Jianguo, D., Kirikkaleli, D., Mentel, G., & Altuntaş, M. (2023). Testing the role of digital financial inclusion in energy transition and diversification towards COP26 targets and sustainable development goals. *Gondwana Research*, *121*, 293–306. https://doi.org/10.1016/j.gr.2023.05.006

Belhaj, R., Ali, N. A., & Browlahrouf, I. (2025). Gamified *Hybrid learning* for Neurodiverse Students: Designing Universally Accessible Instructional Models. *Journal Neosantara Hybrid learning*, *3*(1), 38–46. https://doi.org/10.70177/jnhl.v3i1.2229

Benito, N., Pérez-Martínez, J. C., Roldán, J. B., Lao, Á., Urbina, A., & Serrano-Luján, L. (2025). Life cycle assessment of digital memories: The memristor's environmental footprint. *Sustainable Computing: Informatics and Systems*, *48*, 101229. https://doi.org/10.1016/j.suscom.2025.101229

Dai, S., Su, M., Liu, Y., & Xu, Z. (2023). Digital economy, resource richness, external conflicts, and ecological footprint: Evidence from emerging countries. *Resources Policy*, *85*, 103976. https://doi.org/10.1016/j.resourpol.2023.103976

Dong, X., Dong, D., & Yu, Q. (2024). Impact of oil, gold, and energy prices on resources footprint: Evaluating the role of digital governance and financial development. *Resources Policy*, *92*, 105001. https://doi.org/10.1016/j.resourpol.2024.105001

Dordevic, J., Stojanovi, L., & Markovi, T. (2025). Blockchain-Based Academic Records for Hybrid Education: Securing Digital Credentials in Global Crisis Contexts. *Journal Neosantara Hybrid learning*, *3*(1), 20–28. https://doi.org/10.70177/jnhl.v3i1.2231

Elbadawi, M., Basit, A. W., & Gaisford, S. (2023). Energy consumption and carbon footprint of 3D printing in pharmaceutical manufacture. *International Journal of Pharmaceutics*, *639*, 122926. https://doi.org/10.1016/j.ijpharm.2023.122926

Eliades, T., Adel, S. M., Akyalçin, S., Atsawasuwan, P., Foong, K. WC., Hiskia, A., Panayi, N., Silikas, N., Allareddy, V., Venugopal, A., Dellinger, A., Perillo, L., & Vaiid, N. (2025). Environmental footprints in orthodontics: The World Federation of Orthodontists' white paper on sustainable practices, challenges and research imperatives. *Journal of the World Federation of Orthodontists*, *14*(4), 194–201. https://doi.org/10.1016/j.ejwf.2025.06.003

Farfan, J., & Lohrmann, A. (2023). Gone with the clouds: Estimating the electricity and water footprint of digital data services in Europe. *Energy Conversion and Management*, *290*, 117225. https://doi.org/10.1016/j.enconman.2023.117225

Feng, S., Chong, Y., Yu, H., Ye, X., & Li, G. (2022). Digital financial development and ecological footprint: Evidence from green-biased technology innovation and environmental inclusion. *Journal of Cleaner Production*, *380*, 135069. https://doi.org/10.1016/j.jclepro.2022.135069

Gibbons, S., Watts, C., White, S., & Bach, L. (2025). Investigating awareness and behavioural intentions from AI water footprint digital posters in higher education settings. *Sustainable Futures*, *10*, 101533. https://doi.org/10.1016/j.sftr.2025.101533

Gonzales, S., Fernandez, C., & Wei, L. (2025). Adopting Heutagogy in Non-Formal Education: A Participatory Action Research with Community Learning Centers. *Journal Neosantara Hybrid learning*, *3*(1), 29–37. https://doi.org/10.70177/jnhl.v3i1.2186

Guan, L., Li, W., Guo, C., & Huang, J. (2023). Environmental strategy for sustainable development: Role of digital transformation in China's natural resource exploitation. *Resources Policy*, *87*, 104304. https://doi.org/10.1016/j.resourpol.2023.104304

He, B., Mao, H., Li, T., & Xiao, J. (2023). A closed-loop digital twin modeling method integrated with carbon footprint analysis. *Computers & Industrial Engineering*, *182*, 109389. https://doi.org/10.1016/j.cie.2023.109389

Houziel, C., Prothon, E., & Trinh-Duc, A. (2023). Carbon footprint of general practice: Retrospective case study of GP offices in a rural department of France. *The Journal of Climate Change and Health*, *14*, 100273. https://doi.org/10.1016/j.joclim.2023.100273

Hu, M., Li, Y., Xiong, W., & Yuan, J. (2025). Can digital inclusive finance suppress energy ecological footprint? Moderated mediation effect test based on technological innovation. *International Review of Economics & Finance*, *103*, 104491. https://doi.org/10.1016/j.iref.2025.104491

Jahanger, A., Hossain, M. R., Awan, A., Sunday Adebayo, T., & Zubair Chishti, M. (2023). Linking tourist's footprint and environmental tragedy through transportation, globalization and energy choice in BIMSTEC region: Directions for a sustainable solution using novel GMM-PVAR approach. *Journal of Environmental Management*, *345*, 118551. https://doi.org/10.1016/j.jenvman.2023.118551

Karlilar, S., Balcilar, M., & Emir, F. (2023). Environmental sustainability in the OECD: The power of digitalization, green innovation, renewable energy and financial development. *Telecommunications Policy*, *47*(6), 102568. https://doi.org/10.1016/j.telpol.2023.102568

Khairani, M., Huda, N., Razak, F., & Wulan, D. R. (2025). From Teacher to Facilitator: The Role of Educators in Supporting Heutagogical Practices in Higher Education. *Journal Neosantara Hybrid learning*, *3*(1), 1–9. https://doi.org/10.70177/jnhl.v3i1.2173

Kohli, V., Chakravarty, S., Chamola, V., Sangwan, K. S., & Zeadally, S. (2023). An analysis of energy consumption and carbon footprints of cryptocurrencies and possible solutions. *Digital Communications and Networks*, *9*(1), 79–89. https://doi.org/10.1016/j.dcan.2022.06.017

Lin, W., Wang, C.-W., Li, Y.-J., & Chen, J.-Y. (2025). From green to digital: Exploring the role of ecological footprints on cybersecurity risk. *Energy Economics*, *146*, 108546. https://doi.org/10.1016/j.eneco.2025.108546

Liu, X., Wu, S., Yue, T., & Lyu, W. (2025). Study on the impact mechanism of digital economy spatial network on regional carbon footprint. *Environmental Challenges*, *20*, 101188. https://doi.org/10.1016/j.envc.2025.101188

Liu, Y., & Chen, K. (2024). Integrated effect of financial development and digital trade on resources footprint: Role of and agricultural value added in MINT countries. *Resources Policy*, *90*, 104707. https://doi.org/10.1016/j.resourpol.2024.104707

Long, Y., Chen, G., & Wang, Y. (2023). Carbon footprint of residents' online consumption in China. *Environmental Impact Assessment Review*, *103*, 107228. https://doi.org/10.1016/j.eiar.2023.107228

Magrizos, S. (2025). The dark side of companies' digital transformation: The carbon footprint of online activities. *International Marketing Review*, *42*(6), 1360–1381. https://doi.org/10.1108/IMR-10-2024-0398

Ni, Z., Yang, J., & Razzaq, A. (2022). How do natural resources, digitalization, and institutional governance contribute to ecological sustainability through load capacity factors in highly resource-consuming economies? *Resources Policy*, *79*, 103068. https://doi.org/10.1016/j.resourpol.2022.103068

Niero, M., Rossi, F., Brullo, G., Pooley, T., Deacon, J., Gombac, A., & Frey, M. (2025). A data-driven modular approach to the digitalization of maintenance services: The case study of a Carbon Footprint calculator for Ricoh Europe. *32nd CIRP Conference on Life Cycle Engineering (LCE2025)*, *135*, 818–823. https://doi.org/10.1016/j.procir.2025.01.075

Noodaeng, S., Petchmedyai, P., Janthasen, A., Ponthip, A., Neamhom, T., & Patthanaissaranukool, W. (2025). Comparative carbon footprint analysis of semi-digital and fully digital implant-supported prosthesis fabrication processes. *Environmental Challenges*, *20*, 101294. https://doi.org/10.1016/j.envc.2025.101294

Ren, X., Zhao, M., & Gao, P. (2024). The inverted U-effect of digital financial inclusion on household food carbon footprint in China: The moderating roles of environmental concern and future expectations. *Energy*, *313*, 133727. https://doi.org/10.1016/j.energy.2024.133727

Robvieux, F., Roth, J., Chapuis, C., & Reiter, M. (2022). Insights into EcoScent Compass™, a holistic tool to measure a fragrance's sustainability footprint, based on its intrinsic green properties and environmental impact. *Current Opinion in Green and Sustainable Chemistry*, *33*, 100583. https://doi.org/10.1016/j.cogsc.2021.100583

S., J., Gokasar, I., Deveci, M., Delen, D., Zaidan, B. B., Wen, X., Shang, W.-L., & Kou, G. (2023). Adoption of energy consumption in urban mobility considering digital carbon footprint: A two-phase interval-valued Fermatean fuzzy dominance methodology. *Engineering Applications of Artificial Intelligence*, *126*, 106836. https://doi.org/10.1016/j.engappai.2023.106836

Sindhu, M. I., Naveed, M., & Almulhim, A. A. (2025). From carbon footprints to digital footprints: Return transmission between AI and renewable energy markets. *Sustainable Futures*, *10*, 101529. https://doi.org/10.1016/j.sftr.2025.101529

Škare, M., Gavurova, B., & Porada-Rochon, M. (2024). Digitalization and carbon footprint: Building a path to a sustainable economic growth. *Technological Forecasting and Social Change*, *199*, 123045. https://doi.org/10.1016/j.techfore.2023.123045

Sutton-Parker, J. (2022). Is sufficient carbon footprint information available to make sustainability focused computer procurement strategies meaningful? *17th International Conference on Future Networks and Communications / 19th International Conference on Mobile Systems and Pervasive Computing / 12th International Conference on Sustainable Energy Information Technology (FNC/MobiSPC/SEIT 2022), August 9-11, 2022, Niagara Falls, Ontario, Canada*, *203*, 280–289. https://doi.org/10.1016/j.procs.2022.07.036

Turan, E., Konuşkan, Y., Yıldırım, N., Tunçalp, D., İnan, M., Yasin, O., Turan, B., & Kerimoğlu, V. (2022). Digital twin modelling for optimizing the material consumption: A case study on sustainability improvement of thermoforming process. *Sustainable Computing: Informatics and Systems*, *35*, 100655. https://doi.org/10.1016/j.suscom.2022.100655

Vann, R., Rith, V., & Suyitno, S. (2025). Community-Based Social Education for Sustainable Development – An Indonesian Perspective on Collaborative Learning Models. *Journal Neosantara Hybrid learning*, *3*(1), 10–19. https://doi.org/10.70177/jnhl.v3i1.2174

Wang, C., Zheng, C., Hu, C., Luo, Y., & Liang, M. (2023). Resources sustainability and energy transition in China: Asymmetric role of digital trade and policy uncertainty using QARDL. *Resources Policy*, *85*, 103845. https://doi.org/10.1016/j.resourpol.2023.103845

Wang, Y., Wu, Q., & Razi, U. (2023). Drivers and mitigants of resources consumption in China: Discovering the role of digital finance and environmental regulations. *Resources Policy*, *80*, 103180. https://doi.org/10.1016/j.resourpol.2022.103180

Winter, S., Quernheim, N., Arnemann, L., Anderl, R., & Schleich, B. (2023). Live Estimating the Carbon Footprint of Additively Manufactured Components – a Case Study. *30th CIRP Life Cycle Engineering Conference*, *116*, 642–647. https://doi.org/10.1016/j.procir.2023.02.108

Wu, W., Xu, Z., Zenchenko, S., & Strielkowski, W. (2023). Does sustainable digital economy have implications for climate change? Novel evidence in the context of sustainable energy technologies. *Sustainable Energy Technologies and Assessments*, *60*, 103524. https://doi.org/10.1016/j.seta.2023.103524

Ytreberg, N. S., Alfnes, F., & van Oort, B. (2023). Mapping of the digital climate nudges in Nordic online grocery stores. *Sustainable Production and Consumption*, *37*, 202–212. https://doi.org/10.1016/j.spc.2023.02.018

Zhang, X., Song, X., Lu, J., & Liu, F. (2022). How financial development and digital trade affect ecological sustainability: The role of renewable energy using an advanced panel in G-7 Countries. *Renewable Energy*, *199*, 1005–1015. https://doi.org/10.1016/j.renene.2022.09.028