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Sustainable Digital Education: Green Literacy and Eco-Critical Practices in Technology-Enhanced Learning

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ABSTRACT

Environmental vulnerabilities have been brought about by global technological adoption and improvement, particularly for emerging nations like Pakistan. Sustainable digital education plays a critical role in reducing the negative environmental effects of the fast growing technology. This research study investigates the significance of green literacy, eco-critical pedagogy, and institutional support in realizing sustainable digital practices among learners and educators of secondary and higher educational institutions across the selected four provinces of Pakistan. The quantitative surveys (N=400) showed moderate green literacy (M=3.41) and significantly lower eco-critical attitudes (M=3.12), sustainable digital practices (M=2.94) and institutional support (M=2.51) on a five-point scale. Furthermore, the regression analysis was applied to a cleaned subsample (n=400) and the regression results revealed that green literacy was found to be the strongest predictor of sustainable digital practices (β =.38), followed by eco-critical attitudes (β =.31) and institutional support (β =.27). In addition, the analysis of variance (ANOVA) results highlighted that the model as a whole was statistically significant ($p < .001$) and accounted for 52% of the variance in sustainable behaviors. Considering the cross-sectional and self-reported nature of the data, these findings should be interpreted cautiously and are not indicative of causal relationships. Furthermore, the qualitative interviews with teachers, students and administrators have indicated much interest in the eco-critical approaches, while poor infrastructure, unstable electricity, inadequate professional development and lack of national and institutional policies related to low-carbon ICT and e-waste management remained significant impediments. Overall, the results highlight systemic gaps within the digital education system in Pakistan at both the institutional and policy levels and the clear disconnect between knowledge and action. The present study suggests a comprehensive, context-sensitive approach to sustainable digital education, grounded in developing green literacy, integrating green learning with educational processes, obligatory staff training, and national policy directives. Implementation of such reforms will result in a transformation of the rapidly emerging digital learning in Pakistan to a climate-resilient, energy-efficient and socially responsible ecosystem that is aligned with Pakistan's development agenda for sustainable development.

Keywords: Sustainable Digital Education, Green Literacy, Eco-Critical Pedagogy, Digital Ecological Footprint, Institutional Support, Education Policy, Pakistan

1. INTRODUCTION

The digitization of education has changed the learning environment worldwide, generating debate about the long-term sustainability of technology-enhanced learning systems. As digital tools have expanded instructional modalities and institutions' reach, their rapid and disproportionate adoption has raised concerns about environmental impact, resource dependency, and sustainability, especially in developing contexts. Similarly, educational processes in Pakistan have been driven primarily by the expansion of digital infrastructure, the growing use of internet-based learning, video conferencing, and content delivery via digital assessment systems (Iqbal et al., 2024).

The magnitude, quality, and sustainability of these digital changes were, however, varied among institutions, regions, and socio-economic groups and should not be understood as a comprehensive or equitable digital transformation. Despite bringing some learning opportunities, digitalization also created various challenges such as energy consumption, scarcity of resources, and the environmental impact (Shaaban-Nejad & Shirazi, 2022).

Similarly, digital technologies are connected with a high electricity usage and active replacement of devices, which causes carbon emissions and the formation of e-waste. The environmental costs of digital learning are magnified in Pakistan, where fossil fuel is the most widespread source of power, used in electricity generation, as opposed to other areas with higher consumption of renewable energy (Qureshi & Hussain, 2023; Rehman & Gill, 2023). These concerns are rapidly rising in urgency in Pakistan, a nation facing the threat of climate vulnerability, increasing temperatures, frequent flooding, and energy shortages (Jamil & Muschert, 2023; Talpur et al, 2023).

Therefore, the use of technology in education cannot be evaluated merely based on the concepts of access and efficiency, but also based on its environmental impact, sustainability, and the possibility of encouraging green digital practices. Recent research studies highlight the fact that sustainable digital learning should also be able to bridge the gap between technological advancements and environmental consciousness of both educators and learners (Rehman and Gill, 2023; Akhtar et al., 2025).

Green literacy as a multilayered concept refers to the knowledge, attitudes, and behaviors needed to learn and respond appropriately to environmental issues caused by digitalization. It will allow the learners to assess the effect of their usage of technologies and implement knowledgeable practices that reduce the digital carbon footprints (Aldawsari et al., 2025; Ricoy & Sanchez, 2022). An example of this is that the awareness of the digital mechanisms such as HD video streaming, long charging times and heavy cloud-based storage enables the user to be more responsible. Though green literacy in digital education can carry enormous potential to meet the green sustainability goals of a country, the problem in Pakistan is that many educational institutions do not systematically incorporate green education into digital education, which restricts the realization of sustainability principles into the learning processes (Afzal et al., 2024).

On the pedagogical level, eco-critical pedagogy offers a critical interpretative discourse of the convergence of the digital systems, technological consumption, and online cultures with environmental degradation. Based on the critical theory, eco-critical pedagogy uses environmental ethics to encourage students to resist technological determinism, analyze the socio-environmental consequences of the digital systems, and develop reflection practices that can promote environmental justice (Hajj-Hassan et al., 2024). Technology-enhanced learning in Pakistani context can be empowered by applying the principles of eco-criticism, which, in addition to the conscious use of digital tools, contributes to the perception of the overall socio-ecological cycle involving the production of technology, the extraction of its data, and the disposal of e-waste (Arifeen, 2022).

Although the world is heading towards sustainable digital ecosystems, Pakistan's education sector is not adequately prepared to address the environmental implications of digitalization. The existing policy frameworks, such as the Digital Pakistan Policy, the draft of the National Education Policy, and the Higher Education Commission guidelines, are mostly focused on the development of digital infrastructure without focusing on environmental sustainability (Billet et al., 2025). One of the problems that exist is that there is lack of uniformity in the adoption and documentation of pro-environmental digital practices, including e-waste recycling, sustainable ICT procurement, energy-efficient technologies, and environment-friendly digital practices. Teachers have limited experience with conscientious online teaching, and students are not exposed to sustainability ideas effectively implemented in digital learning systems (Selvarajan & Mahmud, 2025).

At the same time, the demographic situation of Pakistan, where more than 60 percent of the population is under the age of 30, is an important ground for offering digital sustainability skills to them(UNDP, 2018).

Not only are the younger generations the active users of digital tools, but they are also the ones who are the most impacted by the speeding climate crisis. Integrating sustainability in digital learning helps to make students more empowered as accountable digital citizens who take responsibility of the environment.

The current study fills the most pressing gaps by examining how eco-critical pedagogy, sustainability, and green literacy intersect in the context of technology-enhanced learning in Pakistan. It examines the perceptions of students and educators regarding environmental responsibility in online learning, sustainable digital practices, and the institutional barriers they faced. In addition, it evaluates the level of environmental sustainability implementation in Pakistani educational institutions in digital learning policies and practices in teaching. The study suggests a context-based model of sustainable digital education that can be applied in the Pakistani context in terms of socio-economic, environmental, and technological conditions. This research contributes to rethinking the future of learning in Pakistan by including digital education within the broader discourse on environmental sustainability. It presents sustainable digital education as a pathway towards environmental consciousness, responsible use of technology and climate-conscious educational systems. Finally, the results offer evidence-based insights for policymakers, educators, and institutions to develop policies that enhance the development of low-carbon digital ecosystems in line with Pakistan’s climate resilience and sustainable development goals.

2. LITERATURE REVIEW

The digitalization of education is transforming the education context in a fundamental way. Although these technologies will help to increase institutional reach, to facilitate flexible pedagogical models, and to improve instructional delivery, scholars remind us that their widespread use will have significant environmental impacts, such as increased energy use, dependence on infrastructure, and burden on global resource systems (Selwyn, 2021; Jandrić & Ford, 2022). Internet-based learning, cloud computing systems, and digital conferencing platforms have increased the dependency on technology-mediated education (Wirtu & Tucho, 2022) in developing countries like Pakistan (Spangenberger & Söbke, 2025), however, this change is closely correlated with greater electricity use which is typically fossil fuel-based, leading to carbon emissions and higher e-waste production in resource-poor settings (Paredes-Canencio et al., 2024). Such progress underscores the importance of a sustainable digital education paradigm that considers technological advances and ecological responsibility (Singh & Ogunseitan, 2022).

To address these concerns, sustainability literacy frameworks view environmental understanding as a multidimensional experience encompassing knowledge, attitudes, and responsible behavior (UNESCO, 2017). In the context of digitally mediated learning environments, this involves the learners' ability to identify and mitigate environmental effects of digital technologies, namely the eco-digital literacy. The studies, however, show that there is a strong disconnect between awareness and action; that is, people may know about the environment and sustainable practices but do not actually change their behavior (Kollmuss & Agyeman, 2002). This is compounded by the fact that many people don't realize that there are environmental costs associated with digital activities like cloud storage, streaming, and constant connectivity. Therefore, enhancing digital green literacy is crucial to establishing responsible digital citizenship and sustainable interaction with technology (Lozano-Díaz and Fernández-Prados, 2020).

The knowledge–behavior relationship in digital contexts is complex, even as awareness increases. The knowledge-behavior dichotomy of traditional EE holds that gaining knowledge results in behavior change, but digital infrastructures are invisible, making impacts on the environment psychologically distant (Bieser & Hilty, 2018). Digital activity energy usage is embedded in the systems used such as network of cloud computing infrastructure and data centers, which conceal energy usage arising from everyday use (Malmodin & Lundén, 2018). It makes users feel the digital activity is immaterial and obscures the accountability for the environment (Freitag et al., 2021). Hence, it is essential to include digital carbon awareness and the environmental impact of everyday data use in green literacy frameworks.

Individual literacy is a starting point for interacting with digital environments, yet Eco-Critical Pedagogy is broader, looking not only at literacy as an individual skill, but also at technology as a socio-political system (UNESCO, 2021). As part of critical theory, it highlights that ICT is situated within a context of power and inequality (Zou, 2025). Students are motivated to explore the life cycle of digital technologies (extraction, emissions and e-waste) (Parajuly et al., 2019). Reflective inquiry and project-based learning methods can engage teachers and students in building sustainability awareness and contribute to a more sustainable approach to education and transformation for the long-term (Liebhaber et al., 2024).

The shift from instrumental to reflexive models of digital citizenship is necessary for implementing an eco-critical curriculum. In the field of educational technology, the focus is primarily on efficiency and technical aspects rather than on environmental issues (Selwyn, 2021). Postdigital ecopedagogies inspire critical thinking about consumption, replacement cycles of devices and structural inequalities of digital systems (Jandrić & Ford, 2022). Digital technologies also play a role in degrading the environment, creating e-waste that has a disproportionate impact on vulnerable populations (Singh & Ogunseitan, 2022). This reflective learning thus encourages responsible data use and sustainable digital behavior.

Organizational readiness is an important part of eco-critical digital education. The key elements of effective integration in regard to technology, pedagogy, and institutions are green procurement, curriculum integration, and professional development (OECD, 2021). In developing contexts, however, ICT policy is often more about extending the infrastructure than about managing e-waste and responsible use, leading to gaps in the management of e-waste and responsible use (Wirtu & Tucho, 2022). One way to achieve this is through the creation of recycling systems, the application of circular economy principles, and capacity

building programs (Oteng-Ababio et al., 2020). Sustainability initiatives are piecemeal if they are not well institutionalized (Klusmann et al., 2023).

In summary, the alignment of the institutional policy and classroom practices is crucial for successful implementation. Sustainability efforts are inconsistent and subject to operational limitations when there is no strong administrative support (Klusmann et al., 2023). The problems that teachers face when implementing low-energy digital activities often stem from a rigid system that demands high-energy activities (Arifeen, 2022). Institutional leadership and policy integration, such as green procurement and sustainability-related accreditation frameworks, are essential to overcoming these barriers and institutionalizing eco-responsibility as a core norm within the organization (Boud & Soler, 2016).

3. THEORETICAL FRAMEWORK

The current study is based on three related theoretical frameworks: the Green Literacy Theory, the Eco-Critical Pedagogy, and the Digital Education Model. These frameworks offer a comprehensive lens for analyzing low- carbon digital practices, critical evaluation and environmental awareness within Pakistan's technology-enhanced learning environments.

3.1 Green Literacy Theory

The Green Literacy Theory conceptualizes environmental literacy as a multidimensional construct comprising ecological knowledge, environmental attitudes, sustainable behaviors, and socio-environmental responsibility. Researchers stressed that the scope of green literacy expanded environmental consciousness by addressing the capacity to understand how technology affects the environment (Manguil, 2024; Hasibuan et al., 2025). The implementation of green literacy in the digital learning environment must acknowledge the consequences of online activities, including excessive screen time, streaming videos, dependence on cloud storage services, and regular device updates (Buchan et al., 2024).

Digitalization in the education sector is growing rapidly compared with the level of environmental literacy in Pakistan. The development of green literacy is essential for empowering learners to make responsible choices about their digital behavior. Recent studies indicate that students at higher education institutions in Pakistan have moderate levels of environmental awareness and lack information on digital ecological footprints, including mobile network data consumption and e-waste disposal (Begum et al., 2021). Therefore, the first analytical pillar is the Green Literacy Theory, which comprises the strong environmental responsibility as a vital aspect of being a digital citizen.

3.2 Eco-Critical Pedagogy

Eco-Critical Pedagogy builds on environmental education by situating ecological issues within the broader socio-cultural, political, and technological systems. It uses the idea of critical pedagogy to oppose the mainstream discourses of technological advancements and consumerism that lead to environmental degradation (Hajj-Hassan et al. 2024). According to eco-critical educators, digital technologies are not a neutral phenomenon: on the contrary, they condition human relations with the environment, promoting rapid consumption, constant connection, and a replacement culture that stimulates the increase in e-waste (Parajuli, 2020).

The pedagogical integration of eco-critical approaches to technology-enhanced learning in Pakistan will enable educators and students to critically examine the intersectional relationship between digital practices and technological infrastructures and environmental justice concerns. To take concrete examples,

learning how abandoned electronics are disproportionately affecting marginalized populations or how data centers contribute to rising carbon emissions can increase ecological awareness (Arifeen, 2022). Examples of pedagogical practices promoted by eco-critical pedagogy include reflective inquiry, dialogic learning, and project-based learning, which help learners explore the environmental aspects of digital life.

Eco-critical pedagogy can provide a radical solution to educational problems in Pakistan, as the effects of climate change are severe and disproportionate, affecting people unequally. This theoretical prism empowers students and makes them question unsustainable digital practices and think about eco-friendly alternatives (Husamah et al., 2025).

3.3 Sustainable Digital Education Model

The Sustainable Digital Education Model is a synthesis of ecological sustainability and digital pedagogy with three dimensions, including technological sustainability, pedagogical sustainability, and institutional sustainability (Bozkurt and Sharma, 2020; Chang et al., 2025). Technological sustainability focuses on the use of energy-efficient digital tools, low-carbon virtual platforms, and environmentally friendly ICT. As Pakistan faces an energy crisis and relies on non-renewable energy sources, switching to greener digital technologies may significantly reduce the environmental cost of online education (Tobel, 2024).

Pedagogical sustainability advocates embed the ideas of sustainability in the digital curriculum design, pedagogical methods, content development and evaluation of students. As an example, teachers can include environmental case scenarios into online courses, support low-bandwidth tasks, or ask students to analyze the environmental consequences of their online work (Akhtar et al., 2025).

Institutional sustainability deals with policies, infrastructure, as well as capacity-building programs that promote sustainable digital practices. These involve e-waste recycling systems, digital infrastructure planning, and faculty professional development in digital pedagogy that is sustainability-oriented (Billet et al., 2025). In Pakistan, institutional sustainability can be of particular interest since the digital transformation processes have been divided and with no attention to the environment.

3.4 Integration of Theories

The theoretical framework, including green literacy, eco-critical pedagogy, and sustainable digital education, overlaps to constitute the conceptual foundation of the study. Green literacy gives personal-level skills that enable an individual to be environmentally responsible in their use of digital environments. Eco-critical pedagogy improves critical awareness of the socio-environmental consequences of digital technologies on students and teachers. The Sustainable Digital Education framework provides facilities with an ecological outline of how to integrate ecological sustainability within digital learning systems.

Collectively, they direct the study inquiry on the Pakistani students' and teachers' perceptions of sustainable digital practices, the degree to which the eco-critical concepts guide teaching and learning, and the institutional facilitators or challenges to sustainable digital education. The combination of these theories by the research facilitates a comprehensive grasp of the concept of sustainability in digital learning, harmonized with personal actions, teaching practice, and organizational practices in relation to the objective of environmental and digital transformation of Pakistan as a whole.

3.5 Research questions and objectives

The study focuses on the role of green literacy and eco-critical activities in defining digital sustainable education in the technology-enhanced learning context of Pakistan. The following research questions and

objectives are formulated in accordance with the theoretical framework of the Green Literacy Theory, Eco-Critical Pedagogy, and the Sustainable Digital Education Model.

3.5.1 Research Questions

RQ1. What are the levels of green digital literacy and sustainable digital practices among the students and teachers in technology based learning in Pakistan?

RQ2. How are eco-critical pedagogical practices realized in online teaching and learning in Pakistani educational institutions?

RQ3. How sustainable is digital education in Pakistan promoted or inhibited by institutional factors (e.g., infrastructure, policies, professional training, as well as resource provision)?

RQ4. What are the correlations between green literacy, eco-critical pedagogical practices, and sustainable digital practices among students and teachers?

RQ5. What are the ways these empirical findings can be combined to come up with a country-specific model of sustainable digital education in Pakistan?

3.5.2 Research Objectives

1. To determine the extent of green literacy (environmental knowledge, environmental attitudes, and awareness of digital ecological footprint) among students and teachers in Pakistan.

2. To know about the sustainable digital practices adopted by educationists and learners, with the emphasis on low-energy digital habits, e-waste disposal, and responsible use.

3. To investigate the level of eco-critical pedagogical incorporation in the digital teaching practices secondary and higher educational institutions.

4. To determine structural facilitators and obstacles that impact sustainable digital education, such as technological preparedness, policy structures, digital infrastructure, and faculty competency.

5. To discuss the connections between green literacy, eco-critical pedagogy and sustainable digital practices, relying on both quantitative and qualitative findings.

6. To present a Pakistan-specific sustainable model of digital education based on the achievements of empirical research and built on the socio-environmental and technological conditions inherent to the country.

4. METHODOLOGY

4.1 Research Design

The study followed a mixed-methods research design, comprised of quantitative surveys, interviews, and document analysis to obtain in-depth information on sustainable digital education practices in Pakistan. A mixed-methods approach is appropriate for examining the interactions among individual behavior, institutional structure, and socio-environmental context. Therefore, for the current study the mixed-methods design was appropriate to reflect both quantifiable tendencies in green literacy and digital activities (quantitative) and subtle information about pedagogical practices, institutional policies, and obstacles to sustainability (qualitative) (Creswell & Poth, 2021).

4.2 Sampling and sample size

The study followed a multi-stage stratified sampling design, combining stratification with convenience-based institutional access; a technique common in large-scale educational surveys where full probability sampling across geographically distributed populations is logistically challenging (Cohen et al., 2018; Creswell & Creswell, 2018).

The first stage involved stratification of the population based on two dimensions: (a) respondents (students and teachers); and (b) province (Punjab, Sindh, Khyber Pakhtunkhwa and Baluchistan). This stratification was important to ensure representative coverage of regional diversity, and to systematically cover the diversity of digital infrastructure, capacity of institutions and socio-economic contexts that were relevant to sustainable digital education.

In the second stage, educational institutions in each provincial stratum were sampled by convenience sampling due to ease of access, willingness of the institutions to participate and the proximity of the researcher to the institutions, which is in accordance with the pragmatic fieldwork constraints endorsed in the literature (Andrade, 2021; Golzar et al., 2022). Convenience sampling at the institutional level is established and reasonable in cases where there is no institutional list that can be sampled exhaustively and/or when accessing the institutions is limited by resource and access constraints (Etikan et al., 2016).

In the third stage, participants were selected randomly from within each accessible institution, to ensure unbiasedness in the selection of the participants. Also, to avoid regional over- or under-representation and to allow valid comparisons across provinces, 150 participants per province (a total of 600 students) were selected. Similarly, a total of 240 teachers were selected from the same provincial strata from institutions that are accessible for recruitment. Thus, the total sample of (N = 840) was regarded as adequate for the multivariate analyses, such as multiple regression and structural equation modeling, and for the stability of the estimates.

The study recognizes that convenience sampling at the institutional level is a limitation, as the study results may have limited external generalizability to other institutions. However, this limitation is significantly reduced by the stratified design at the population level and the random sampling at the participant level, which allows for representativeness across key demographic and regional dimensions.

In the qualitative part, participants were selected through purposive sampling to ensure inclusion of individual with relevant experiences in education through digital technology and in the implementation of policies. A sample of 40 teachers, 40 students, and 20 administrators was deemed to be sufficient for thematic analysis, as it ensured that a broad range of experiences, institutional practices and policy perspectives were represented, but not for statistical generalization (Guest et al., 2006; Braun & Clarke, 2021). The participants were selected based on their activities in technology-enhanced teaching, sustainability, or digital policy implementation and administration at institutions. While following the procedures outlined by Guest et al. (2006) and Saunders et al. (2018), data collection continued until the themes, including green literacy, eco-critical pedagogy, sustainable digital practices, and institutional support, became saturated and stable, with no new insights emerging meaningfully in the subsequent interviews.

Table 1 (A). Quantitative Sample (n = 840)

Variable	Category	Students (n=600)	Teachers (n=240)	Total (%)
Gender	Male	320	130	450 (53.6%)
	Female	280	110	390 (46.4%)
Province	Punjab	150	60	210 (25%)
	Sindh	150	60	210 (25%)
	Khyber Pakhtunkhwa	150	60	210 (25%)

Variable	Category	Students (n=600)	Teachers (n=240)	Total (%)
	Balochistan	150	60	210 (25%)
Age Group	18–25	420	20	440 (52.4%)
	26–35	160	90	250 (29.8%)
	36–45	20	90	110 (13.1%)
	46+	0	40	40 (4.7%)
Education Level	Intermediate	220	0	220 (26.19%)
	Bachelor	280	40	320 (38.0%)
	Master	70	140	210 (25%)
	MPhil/PhD	30	60	90 (10.8%)
Experience	<5 years	0	80	80 (33.3%)
	5–10 years	0	90	90 (37.5%)
	10+ years	0	70	70 (29.2%)

Table 1 (B). Qualitative Sample (n=100)

Category	Participants (n)	Gender (M/F)	Key Characteristics
Teachers	40	22 / 18	Experienced in digital/technology-enhanced teaching
Students	40	20/20	Enrolled in technology-enhanced learning; experienced with digital academic practices
Administrators	20	13 / 7	Involved in ICT policy, academic planning, or digital implementation
Total	100	55/45	

4.3 Measurement and Data Collection

4.3.1 Quantitative Surveys

A structured questionnaire was prepared to measure:

1. Green Literacy - environmental awareness, awareness of online carbon footprint, and an environmental attitude towards the use of technology that is sustainable.
2. Sustainable Digital Behaviors: measurable consumption frequency of low-energy digital use, managing e-wastes, responsible use of devices, and patterns of consuming digital devices.
3. Eco-Critical Pedagogy Awareness: Self-reported environmental reflection and critical digital literacy implementation in instruction by teachers.
4. Institutional Support- perspectives of policies, training prospects and infrastructure that underlies sustainable digital education.

The questionnaires were adapted from existing, validated instruments in the following domains: Environmental literacy, Sustainability behavior, and Digital education, with some amendments to suit the

socio-educational context of Pakistan. Contextualization of the items has been carried out carefully to reflect the technological practices, institutional context and digital access levels in the area.

The Green Literacy construct was adapted from validated environmental literacy scales, such as the one used by Lichtveld et al. (2019), to encompass knowledge, attitudes, and responsible behaviors regarding the environment, and was extended to include technology-related impacts on the environment (Gerick et al., 2019).

The Sustainable Digital Behaviors were influenced by the new digital sustainability frameworks and by recent institutional adaptations that focus on energy efficiency and responsible digital consumption, as presented in Barragán-Sánchez et al. (2020) validated instrument.

Eco-Critical Pedagogy Awareness was based on the frameworks of digital competence and sustainable development education as presented in UNESCO's 2024 agenda for Education for Sustainable Development and other recent studies on digital ecoliteracy (Hasibuan et al., 2025) which emphasized critical thinking, ethical uses of digital tools, and the importance of pedagogy for sustainability.

Institutional Support was assessed using approved instruments from educational technology and organizational research, including those of Philipsen et al. (2021) and Zhao et al. (2020), which involve policy support, training programs and technological infrastructure for sustainable digital practices.

Data was collected on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree). Before collecting data, a pilot study was conducted through a convenience sampling technique while collecting data from 50 students and 20 teachers from secondary and higher educational institutions. The pilot study aimed to test the clarity and readability of the survey items, as well as test the reliability and validity of the survey items. Based on the pilot survey findings, the survey items were refined to improve comprehension. Additionally, Cronbach's alpha was used to measure the internal consistency of the instrument and the results highlighted that the internal consistency of the scale ranged between 0.75 and 0.79 (Green Literacy = 0.79, Sustainable Digital Behaviors = 0.76, Eco-Critical Pedagogy Awareness = 0.78, Institutional Support = 0.75), which reflects the acceptable reliability results for carrying out research (Taber, 2018).

4.3.2 Qualitative Interviews

Qualitative data were collected through semi-structured interviews with teachers, students, and administrators, along with an analysis of policy documents related to digital education in Pakistan. Semi-structured interviews were conducted with 40 teachers to explore their views on sustainable digital practices, 40 students to understand their perceptions of eco-critical digital practices, and 20 administrators to examine their perspectives on institutional and policy support. Participants were selected through purposive sampling based on their professional roles, experience in digital education, and involvement in sustainability practices or policy implementation. Efforts were made to include participants from diverse institutional and regional backgrounds to ensure a broad range of perspectives.

The interviews focused on:

- Policies and programs of institutional sustainability of digital education.
- Obstacles and impediments to eco-critical teaching.
- Views on the inclusion of green literacy in the curriculum.

4.3.3 Document and Policy Analysis

Documents of the nation and institutions were examined, such as:

- Digital Pakistan Policy (2021–2025)
- Guidelines on ICT within Higher Education Commission.
- University online policies and sustainability reports.

Documents were selected for relevance, recency, and direct connection to digital education, sustainability, and policy implementation. Systematic content analysis was used, including open and thematic coding based on the study constructs: green literacy, sustainable practices, eco-critical pedagogy, and institutional support.

The analysis was based on identifying the priorities, implementation strategies and gaps concerning sustainable digital education in the policy. The documents were used to derive key themes, which were compared with information from the interviews to ensure triangulation and the credibility of the results.

4.4 Data Analysis

SPSS 28 was used to analyze quantitative data. The levels of green literacy, eco-critical awareness, and sustainable behaviors were evaluated using descriptive statistics (mean and standard deviation). Correlations between variables were analyzed to determine whether sustainable digital behaviors were predicted by green literacy, eco-critical pedagogy, and institutional support.

Data screening was conducted on the entire original sample (N = 840, including 600 students and 240 teachers) prior to data analysis. The full sample (N = 840) was used for descriptive analysis and bivariate correlation to provide a complete picture of the data by following the recommended practice that the exploratory stage would retain as much statistical information as possible (Tabachnick & Fidell, 2019)

As, multiple linear regression requires more stringent assumptions in respect to missing data, multivariate normality, and outliers. Therefore, the following exclusion criteria were used in screening the cases before regression analysis was conducted:

- **Missing data:** 187 cases were excluded based on more than 10% of data missing.
- **Incomplete questionnaires**: Questionnaires with one or more sections that were not completed; therefore, 63 cases were excluded.
- **Patterned or straight-line responses:** 89 cases were excluded as the responses were patterned or straight-line, as identified through consistency checks.
- **Multivariate outliers**: Multivariate outliers were detected using Mahalanobis distance ($p < .001$), resulting in the exclusion of 101 cases.

This sequence screening led to the elimination of 440 cases, leaving N = 400 cases for regression analysis. This is a valid descriptive statistics reporting approach to the larger screened sample and an inferential analysis approach to the cleaned subsample and is methodologically justified and transparently documented (Hair et al., 2019; Pallant, 2020). The final regression sample was N = 400 which satisfied the recommended criteria for regression samples ($n \geqslant 10$ – 20 cases per predictor, (Tabachnick & Fidell, 2019), and the rule of thumb ($N \geqslant 50 + 8m$ (Green, 1991).

Furthermore, tests for assumptions of multiple linear regression, such as sufficiency of sample size, normality, multicollinearity, and homoscedasticity, were carried out to test the robustness of the multiple linear regression model.

NVivo 14 was used to code qualitative data thematically. Thematic analysis was used to identify patterns and insights from audio recordings and transcribed interviews. Themes comprised the institutional support, the pedagogical practices, challenges, and suggestions to keep digital education sustainable.

Findings were then integrated using a convergent parallel mixed-methods research design to compare and triangulate quantitative and qualitative results, generating a comprehensive, in-depth understanding of sustainable digital education practices.

4.5 Ethical Considerations

Ethical approval for this study was obtained from the Institutional Review Board of the Department of Sociology, University of Peshawar, Pakistan. Informed consent was obtained from all participants prior to data collection, and strict measures were taken to ensure confidentiality and data protection. Participation in the study was entirely voluntary, and respondents were free to withdraw at any stage without any consequences. Privacy and anonymity were maintained by anonymizing survey responses and interview transcripts throughout the research process.

4.6 Limitations of Methodology

Although the mixed-methods design is more comprehensive, the study may be limited by factors such as reliance on self-reported behaviors, regional bias due to differences in access, and the inability to generalize the results to all educational institutions in Pakistan.

5. RESULTS AND DISCUSSION

5.1 Results

Before presenting the findings, it is essential to note the analytic sample sizes used in each analysis presented in this section. Descriptive statistics (means, standard deviations, frequencies) and bivariate correlation analyses in Table 2 are based on the entire sample (N = 840; 600 students and 240 teachers), as these statistics do not require the same distributional assumptions as regression, and a large sample size improves representation.

However, multiple linear regression analyses were carried out on a cleaned subsample of (N = 400), after systematically dropping 440 cases that did not fulfill the data quality and multivariate assumption criteria (see Section 4.4 for the complete data quality and multivariate assumption check criteria). This distinction is adhered to throughout Section 5 and in all relevant tables is clearly indicated.

5.1.1 Descriptive Statistics

Table 2 presents descriptive statistics of the variables being studied. The findings showed fairly moderate scores in the four measured constructs, with significant differences in their comparative level. Across the four measured constructs, Green Literacy has the highest mean score (M = 3.41, SD = 0.78), indicating that students and teachers have a relatively high level of knowledge and awareness of environmental concerns and sustainability concepts. The Eco-Critical Attitudes are also within the moderate range (M = 3.12, SD = 0.81), indicating that most participants exhibit some level of critical awareness of ecological issues; however, this is not a firmly established awareness. The correspondingly slightly greater

standard deviation is because of the varied attitudinal orientations; some of the people were quite eco-critical, and others were slightly involved. In contrast, sustainable digital behaviors were the lowest domain adopted, with a mean score of (M = 2.94, SD = 0.66). It means that the practices and activities associated with the use of digital technologies (e.g., screen time and cloud storage, e-waste management) are limited in terms of practical and environmentally friendly habits and actions. Finally, Institutional Support records the lowest mean (M = 2.51, SD = 0.71), This finding greatly emphasizes the evident absence of support mechanism tools, such as proper policies, resources, and training in provisions to appropriately integrate sustainable operations into the learning computerized platform.

Overall, the findings suggest a downward trend in knowledge (highest), followed by attitudes (moderate), behaviors (lower), and lastly, institutional support (lowest). This trend highlights the possible disconnection between personal consciousness and reality, which was probably caused by the lack of systemic support of sustainability-oriented digital activity.

Table 2. Descriptive statistics (N = 840)

Variable	Mean	SD	Minimum	Maximum
Green Literacy	3.41	0.78	1	5
Eco-Critical Attitudes	3.12	0.81	1	5
Sustainable Digital Behaviors	2.94	0.66	1	5
Institutional Support	2.51	0.71	1	5

5.1.2 Correlation Analysis

Table 3 shows that the variables under study exhibit several theoretically significant relationships. Green literacy and eco-critical attitudes had the highest correlation ($r = .61$, $p < .01$), which suggests a strong positive relationship. This implies that those who possess a more developed green literacy level have a significantly greater chance of acquiring a critical attitude toward the environmental consequences of digital and educational practices. This highlights the importance of environmental knowledge as the basis of values and critical orientations towards sustainability.

In addition, moderately positive correlations of green literacy and green sustainable behaviors ($r = .49$, $p < .01$) and of eco-critical attitudes and green sustainable behaviors ($r = .57$, $p < .01$) were indicated that the knowledge and attitudes are significant, but the practical implementation of them is dependent on other contextual or institutional factors. It is interesting to observe that institutional support also had a moderate relationship with all variables, particularly with sustainable behaviors ($r = .45$, $p < .01$), suggesting that supportive policies and infrastructure can be used to improve the performance of sustainability-oriented behaviors. Overall, these results indicate the interrelated but segregated roles of literacy, attitudes, behavior, and institutional context in promoting sustainable digital education.

Table 3. Correlation Matrix

Variable	1	2	3	4
1. Green Literacy	1	.61**	.49**	.37**
2. Eco-Critical Attitudes	—	1	.57**	.42**
3. Sustainable Behaviors	—	—	1	.45**
4. Institutional Support	—	—	—	1

Note. Bivariate correlation coefficients are based on the full screened sample (N = 840), p < .01

5.1.3 Assumptions testing for regression analysis

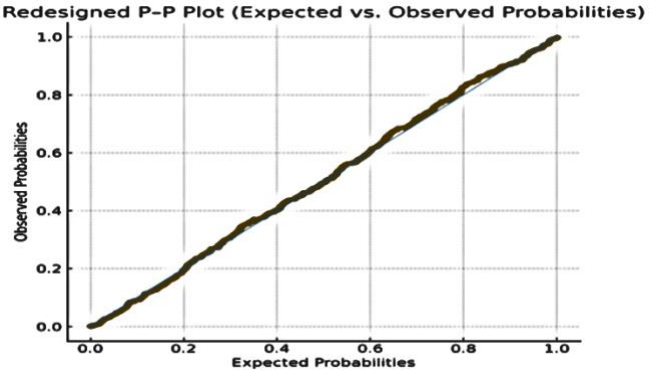
5.1.3.1. Sufficiency of sample size.

The sample of 400 was used to check whether it was sufficient to estimate three variables that were tested to determine their ratio, which was calculated as 1:133, satisfying the minimum ratio of 1:20; the state of sufficiency of the sample size was satisfied (Kline, 2016). Therefore, the sample size is adequate to conduct regression analysis.

5.1.3.2 Linearity

To evaluate linearity, standardized residuals were plotted against each predictor (green literacy, eco-critical attitudes, and institutional support) and sustainable digital behaviors. The P-P plot showed a nearly linear trend (Figure 1), with only a few points positioned slightly above or below the (imaginary) reference line, indicating approximately linear relationship. Therefore, the assumption of linearity was satisfied (Ernst and Albers, 2017).

Figure 1



5.1.3.3 Multicollinearity

Variance Inflation Factor (VIF) and Tolerance were calculated to assess multicollinearity among the predictors. The VIFs are all less than 5 and the tolerances are greater than 0.1 (Table 4), which means that there are no multiple relations between the predictor variables, so the condition of multicollinearity was satisfied (Bowerman and Connell, 1990; Kim, 2019).

Table 4. Multicollinearity

Predictor	VIF	Tolerance
Green Literacy	1.89	0.53
Eco-Critical Attitudes	2.11	0.47
Institutional Support	1.72	0.58

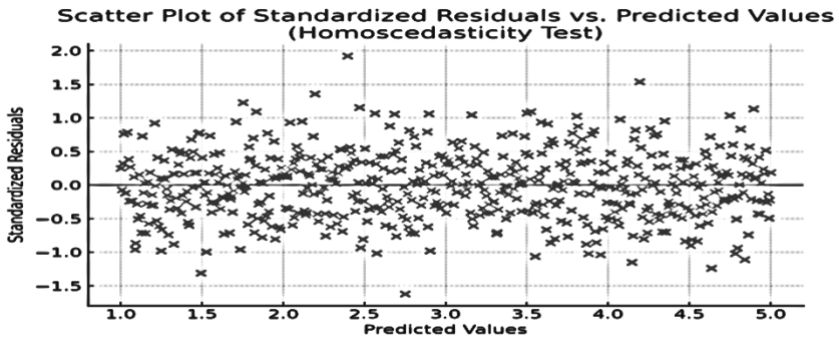
Since all four assumptions (multicollinearity, normality, linearity, and homoscedasticity), along with sufficiency of the required sample size, have been satisfied, the dependent and independent variables are adequate for the next step of performing multiple regression analysis.

5.1.3.4 Homoscedasticity

The scatter plot of standardized predicted values versus the standardized residuals indicates a random and equal distribution of the residual in and about the zero reference line. There is no funnel-shaped distribution, no clustering, and no systematic widening or narrowing across the range of predicted values (Figure 2). This homogeneous dispersion means that the variance of the residuals does not change as the range of predictions widens.

These visual features affirm that the homoscedasticity assumption of the regression model is met.

Figure-2



5.1.4 Regression Analysis

Multiple regression analysis was conducted to determine the predictive impact of green literacy, eco-critical attitudes and institutional support on sustainable digital behaviors.

The main predictions to sustain digital practices sustainably were done via multiple regression using green literacy, eco-critical attitudes and institutional support.

5.1.4.1 Regression Coefficient

Multiple regression analysis was conducted to determine the predictive impact of green literacy, eco-critical attitudes and institutional support on sustainable digital behaviors. Table 5 showed that the three predictors had a significant positive effect ($P < 0.05$) on sustainable digital practices. In particular, the green

literacy turned out to be the strongest predictor (β =.38, 95% CI [.30, .46]), which means that the more knowledgeable and environmentally aware the participants are of environmental ideas, the higher the likelihood of sustainable digital practices. Followed by, Eco-critical attitudes that were found to have a significant positive correlation (β = .31, 95% CI [.21, .41]) signifying that people with a more critical attitude toward environmental issues are more inclined to exhibit sustainable digital behaviors.
Institutional support (β = .27, 95% CI [.15, .39]) also contributed to sustainable digital practices, emphasizing the importance of organizational infrastructure, policies, and training programs in promoting them.

In conclusion, the results indicate that the individual-level factors (green literacy and eco-critical attitudes) and the organizational-level support are all shown to contribute to sustainable digital behavior.

Table 5. Regression coefficients as outcome of sustainable digital behaviors

Predictor	B	SE	t	p	95% CI (LL, UL)
Green Literacy	.38	.04	9.50	<.001	(.30, .46)
Eco-Critical Attitudes	.31	.05	6.20	<.001	(.21, .41)
Institutional Support	.27	.06	4.50	.001	(.15, .39)

Note. The cleaned analytic subsample (N = 400) was used for the reported regression analysis, as 440 cases were systematically excluded in regression analyses that failed to meet the criteria of data quality and multivariate assumption. Listed in detail in Section 4.4.

5.1.4.2 Model Summary

The regression model shows a strong explanation of sustainable digital practices behaviors. In Table 6, the coefficient of correlation (R = .72) shows that there is a strong positive association between the predictor variables (green literacy, eco-critical attitudes and institutional support) and the dependent variable (sustainable digital practices behaviors). The coefficient of determination ($R^2 = 0.52$) indicates that the predictors included in the model account for 52% of the variance in sustainable digital practices behaviors.

The adjusted R^2 value (.51) is slightly lower than the R^2 (.52) as expected. The minimal difference indicates good model stability, reasonable generalizability, and little evidence of model inflation.

The standard error of the estimate (SE) is .40, indicating a relatively low prediction error and a fairly precise fit between the actual values and the model's predictions.

Overall, the results show that the model is robust and explanatory for behaviors of sustainable digital practices. The unexplained variance may be due to other contextual or individual factors that were not included in the model.

Table 6. Model Summary

Model	R	R^2	Adjusted R^2	Std. Error
1	.72	.52	.51	.40

5.1.4.3 Analysis of Variance (ANOVA)

The ANOVA results, $F(3, 396) = 142.36$, $p < .001$, indicate that the regression model is significant. Based on these findings, it was concluded that the joint effects of green literacy, eco-critical attitude, and institutional support significantly predict sustainable digital practices. The results highlighted that the regression model accounts for a significant amount of variance in the dependent variable and is suitable for predicting sustainable digital practices behaviors.

Table 7. ANOVA

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	68.36	3	22.79	142.36	.000
Residual	63.40	396	0.16		
Total	131.76	399			

5.2 Qualitative Findings

5.2.1 Educator Views on Sustainable Digital Practices

The importance of awareness of environmentally responsible practices emerged as a dominant theme during interviews with educators across the four provinces. Teachers recognized that the overuse of data-intensive applications, constant device charging, and outdated digital equipment all negatively impact the environment. This was reflected in participant narratives, for example:

"Students are spending hours in streaming videos and using multiple devices without realizing how much energy they are using. Even in schools, there is little discussion of the impact of technology usage on the environment" (Teacher 07, Punjab).

Educators also pointed to infrastructural barriers in relation to sustainable digital practices:
"While we would like to use green digital practices, electricity issues, poor internet connections, institutional support issues, etc. make it difficult" (Teacher 14, Khyber Pakhtunkhwa).

Using a thematic coding approach in NVivo, major categories emerged, such as digital energy use, infrastructural limitations and institutional guidance. Some teachers stated that digital learning activities incorporating environmental reflection raised students' environmental awareness. One teacher commented:

"It is a different scenario when students think critically about e-waste and digital pollution and take responsibility in the use of technology" (Teacher 03, Sindh).

Nevertheless, participants continued to emphasize that there are still no opportunities for professional development and curriculum support to effectively implement eco-critical teaching practices.

5.2.2 Perceptions of Student Eco-Critical Digital Practices

Student participants (n=40) reported concerns about increased energy use for streaming TV, gaming or extended screen time, which was reflected in the students' responses:

"I know that using devices for a long time consumes electricity, but I don't know the ways to reduce our digital waste" (Student 11, Balochistan)

Thematic analysis revealed a clear disconnect between environmental consciousness and digital actions. Students had positive attitudes towards sustainability, but they felt that there was a lack of concrete advice on how to engage in sustainable practices with digital tools. This was reflected in the following statement:

"We hear about climate change and sustainability but no one tells us that the things we do online also impact the environment" (Student 18, Punjab)

Another consistently raised theme across interviews was institutional and teacher support. Students thought that educational institutions should actively play a role in raising awareness about sustainable digital behavior. One interviewee explained:

"Teachers should guide us on how to use technology in an eco-friendly way such as avoiding unnecessary cloud storage and proper management of e-waste" (Student 09, Sindh)

While conducting the interviews with students, three main topics were identified through the thematic coding, namely, environmental consciousness, unsustainable digital practices, and institutional guidance.

5.2.3 Supportive Institutions and Policy

The majority of institutions did not have policy provisions in relation to eco-friendly use of ICT, e-waste management and sustainable procurement of digital products as illustrated by the following response:

"Extension of digital access and efficiency focus are primarily done while there is still no institutional digital policy on sustainability" (Administrator 04, Punjab)

The analysis also revealed no coordination or consistency among departments in sustainability initiatives. This fragmentation was also highlighted by another administrator:

"Some departments are doing work on a very isolated level; there is no institutional work for sustainable Digital Education at all" (Administrator 02, Sindh)

Themes identified included policy gaps, lack of coordinated sustainability planning, and limited infrastructure. Participants recognized the importance of increased institutional investment and dedication,

infrastructure investments, and policy integration for environmentally sustainable digital transformation. One administrator summed up this concern as follows:

"In the absence of undue policy guidance and institutional funding, sustainability will not be a top priority for digital education" (Administrator 06, Khyber Pakhtunkhwa)

5.2.4 Integration of Perspectives

The qualitative results indicate a general trend among the teachers, students, and administrators: they are all aware of sustainable digital practices, are intrinsically motivated and mindful, but still cannot implement them practically due to constraining structural and institutional factors. There are positive intentions among both teachers and students to go greener and use eco-critical approaches and green literacy programs, but without policy support, sufficient resources, and sustainable development of personal skills, the practices stay mostly only wishful. The responses broaden the point of interpersonal sensitization, pedagogy initiatives, and institutional preparedness to develop sustainable digital learning opportunities in Pakistan.

6. DISCUSSION

The conclusions of the proposed research demonstrate the complexity of digital sustainability in Pakistan, as green literacy, eco-critical pedagogy, and institutional encouragement play important roles in shaping sustainable digital practices. Both quantitative and qualitative data show that awareness of environmental concern among students and teachers is at a level where there is a visible gap between awareness and actual practice.

Sustainable digital behaviors in this study refer to environmentally responsible practices associated with the use of digital technologies, including energy-conscious digital habits, responsible device use, management of digital waste, and eco-friendly digital consumption patterns.

6.1 Green Literacy and Digital Behavior

This quantitative study found that students (M=3.41) and teachers had moderately high green literacy, whereas the rating for sustainable digital behaviors was lower (M=2.94). Such a gap suggests that environmental knowledge does not necessarily lead to the development of environmentally friendly digital behavior. These findings are consistent with past studies indicating that awareness alone cannot affect behavioral change (Asif et al., 2023; Buchan et al., 2024). The regression analysis also showed that green literacy is an important predictor of sustainable digital behavior ($\beta = 0.38$), underscoring its role as a major factor underpinning environmentally sustainable digital behavior.

These findings were further supported by qualitative interviews, in which teachers reported being aware of environmentally harmful digital practices but lacking the resources and institutional support to implement sustainable strategies. On the same note, learners shared that they were interested in minimizing their digital ecological footprint, but they lacked awareness of how to do this and were unsure of the specific actions they could take. These findings are consistent with studies by Ntorukiri et al. (2022) and Chang et al. (2025), which found that barriers to technology adoption include unequal technology infrastructure, a lack of training resources, and high implementation costs.

6.2 Eco-Critical Pedagogy and Reflective Practice

Eco-critical pedagogy was initiated as one of the most important processes for translating cognition into action. This was found to be a moderate relationship (r=.57) between eco-critical attitudes and sustainable digital practices, and the teachers' qualitative narratives indicated the possibility of introducing the concept of critical thinking about environmental effects into digital learning. Teachers recommended that project-based exercises, discussions, and assignments with a special focus on technology's environmental footprints may increase students' involvement and accountability. This result confirms the theoretical claim that reflective and critical pedagogies can solidify environmentally conscious practices in technology-mediated learning settings (Khalifé et al., 2022; Lowan-Trudeau, 2023).

Nonetheless, in the practical implementation of eco-critical pedagogy, considerations of structural barriers would limit implementation. The lack of professional growth and curricular support became the focal point of discussion among teachers as impeding factors to the adoption of eco-critical approaches, which correlates with previous studies revealing institutional constraints in Pakistan (Veletsianos et al., 2022; Shah et al., 2021; Kazazoglu, 2025).

6.3 Supportive Institution as a Facilitating Force

The lowest rating variable of the survey was the institutional support (M=2.51), which highlights the limited infrastructural, policy, and training systems available to facilitate sustainable digital practices. It was found that institutional support is a significant predictor of sustainable digital behaviors ($\beta = 0.27$), highlighting its role as a key enabling factor. Qualitative interviews also demonstrate that experiencing systemic limitations: digital initiatives are mostly focused on access and efficiency but little on environmental factors, and organized systems to regulate e-waste disposal are insignificant. These results indicate that personal awareness or pedagogical novelty alone is ineffective, and that environmentally accountable digital education needs to be supported at the institutional level. Appropriate alignment of policies, professional training, and investment in low-carbon digital infrastructure can help bridge the gap between eco-critical awareness and practice and demonstrate the vitality of organizational capacity in supporting the implementation of digital sustainability (Billet et al., 2025; Chang et al., 2025).

7. CONCLUSION AND RECOMMENDATIONS

This study involved an analysis of incorporating environmental sustainability into digital education systems in Pakistan. The study reveals limited evidence of the parallel integration of environmental sustainability within existing digital education systems, indicating a structural gap in current system design. However, the results of the study based on a cross-sectional design and self-reported data should be seen as suggestive rather than causal or entirely generalizable. Students and educators have some basic awareness of environmental concerns; sustainable digital engagement is not consistently practiced in institutional settings. The trend highlights a disconnect between awareness and intentions to accept environmentally responsible actions on the one hand, and institutional capacity on the other.

One of the most notable contributions of this study is that green literacy, eco-critical pedagogy, and institutional support function as an integrated system rather than isolated constructs. Green literacy offers a necessary baseline, but its impact cannot be realized without supportive policies, professional training and infrastructural preparedness. In the same way, eco-critical pedagogical practices are limited when institutions lack the resources, incentives, and regulatory structures to support environmentally conscious

digital practices. The findings indicate a high likelihood that individual-level sustainability efforts without systemic change will fail to achieve meaningful and lasting results.

Furthermore, the qualitative findings highlighted that the contextual barriers to digital sustainability in Pakistan include poor energy and ICT infrastructure, limited faculty development, and a lack of binding policies on green ICT procurement and e-waste disposal. The current national and institutional policies are still largely geared towards accessibility, effectiveness and technological innovation with limited attention to environmental responsibility.

This imbalance constrains the prospect of digital education, climate resilience and sustainable development agendas.

These findings do not lend themselves to definitive policy conclusions but suggest several directions for policy Action, as outlined below and based upon these findings, and acknowledging the exploratory nature of the evidence. First, it is necessary to integrate green literacy into the existing digital education course instead of treating as supplementary content. Secondly, appropriate faculty development structures should be designed to build teachers' capacity in eco-critical pedagogy. Third, institutional frameworks for the procurement of ICTs should gradually shift towards sustainability. Fourth, a coherent national standard (NSS) for sustainable digitalization in education could be developed to give regulatory clarity and institutional accountability. Combined, these directions suggest that digital education in Pakistan could be reframed as an environmentally-friendly program with environmental values pursued as an integral part of the development agenda instead of being part of the result.

These recommendations are developed from policy directions based on current evidence and should be considered starting points for additional empirical research, not prescriptions for change.

8. THEORETICAL IMPLICATIONS

The current work makes an important theoretical contribution to the growing body of research in sustainable digital education by empirically testing and extending existing conceptual frameworks. First, the results challenge the linear, knowledge-based model of green competence by showing that green literacy alone is insufficient to generate sustainable digital practices unless it is facilitated by eco-critical pedagogical practices and supportive organizational frameworks. This advances theoretical conceptualizations of environmental competence by redefining it as a relational, multidimensional construct rather than a cognitive attribute of the individual. Second, the researchers reinforce the theoretical foundation of eco-critical pedagogy not only in terms of curricular content but as a transformative learning process that mediates the connection between environmental knowledge and behavioral implementation enactment. Thus, the study contributed to eco-pedagogical theory by empirically demonstrating how critical reflection, moral thinking, and situational awareness help overcome the long-standing knowledge-action gap in sustainability education.

Third, the study contributes to systems-based approaches to educational change by highlighting the theoretical attention to institutional support, including policy structures, digital structures, and faculty preparedness, to impact sustainable digital practices. The results suggest that individual-level knowledge and pedagogical innovation will barely lead to the sustained behavioral change unless there is organizational readiness and hence reinforce and expand institutional and socio-technical perspectives of sustainability shifts.

Taken together, these results indicate a holistic and integrative theoretical framework for sustainable digital education, particularly in the context of developing countries such as Pakistan, where structural

conditions are a robust conditioning factor for individual agency. The paper offers a theoretically informed description of the understanding of sustainability-related digital transformation in education, and empirically relates green literacy, eco-critical pedagogy, sustainable digital behavior, and institutional support.

9. PRACTICAL IMPLICATIONS

This research provides a variety of practical implications for instructors, policymakers and institutions who may seek to use sustainable online learning in Pakistan. To begin with, (1) universities and schools should encompass green literacy courses into curricula so that students are aware of digital technology and their effects on the environment and embrace green, eco-friendly behaviors, including using energy-efficient devices, having an optimized cloud server, and disposing of e-waste responsibly. (2) Teachers should be offered professional development programs to use eco-critical pedagogy, enabling them to teach students to think critically about the socio-environmental impacts of digital technologies. (3) The policies at the institution, especially regarding e-waste management issues, need to focus on sustainable ICT infrastructure that becomes low-energy devices, uptake of renewable energy, and formal e-waste management initiatives. (4) education authorities, both nationally and provincially, must be able to institute regulation structures and incentives to promote environmentally-conscious digital education, to match the alignment of institutional practices to climate and sustainability targets. (5) involving the student in real-life sustainability projects in the digital learning setting can enhance the adoption of behavior and promote innovation and environmental stewardship.

All these strategies can bridge the gap between knowledge and practice and foster a sustainable culture of digital learning in Pakistan.

10. LIMITATIONS

Although this study was carefully designed to investigate green literacy, eco-critical attitudes, and sustainable digital behaviors in Pakistan, several limitations should be acknowledged. First, the study relied on self-reported surveys, which may be subject to social desirability bias, as participants could overstate environmentally responsible behaviors. Second, although participants were randomly selected from within accessible institutions, the institutions themselves were selected through convenience sampling across four provinces due to practical access constraints. While this approach provided geographic diversity, it may limit the generalizability of the findings to all educational institutions in Pakistan. Third, although the mixed-methods design enriched the findings, resource constraints restricted the number of qualitative interviews conducted, potentially omitting additional contextual factors that influence sustainable digital education. Fourth, the cross-sectional design captures data at a single point in time, limiting the ability to evaluate longitudinal changes in knowledge, behavior, and institutional practices. Fifth, external factors such as regional energy availability, socio-economic inequalities, and climate-related issues could have affected participants' sustainable digital behaviors beyond the study framework.

In addition to these methodological restrictions, some restrictions of the literature used should also be mentioned. Most of the previous research studies were conducted in a Western or technology-advanced setting, which might render the direct applicability and usefulness of their findings to the Pakistani educational system. Moreover, discrepancies in operationalization, scales of measurement, and reporting across the different studies discussed could lead to slight inconsistencies in the interpretation of the results during the synthesis. The research has incorporated the empirical and referential limitations, hence

providing a more transparent and balanced description of the scope, and this has contributed to the credibility and interpretive rigor of the research.

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Conflict of Interest

The authors assert that they are not aware of any competing financial interests or any other personal relationships that would have led to the work that was reported in this paper.

Data Availability Statement

The data that justify the findings of this study can be obtained from the corresponding author on reasonable request. The information is not made public due to the privacy and confidentiality concerns of the students and the institutions involved.

Use of AI Tools

The only use of AI-assisted language support was to enhance the manuscript's grammar, word processing, readability, and clarity. It was not utilized to produce research data, statistical analysis, results, or to substitute the scholarly judgment of the authors. The authors revised, edited, and approved the final manuscript and have absolute responsibility for its contents.

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