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RESEARCH ARTICLE **Section:** *Digital Humanities*

Digital humanities for green pedagogy: Embedding environmental sustainability (SDGs 4, 13)

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ABSTRACT

This synthesis of forty studies examines the pivotal role of digital humanities (DH) tools in advancing green pedagogy and education for sustainable development. The research demonstrates how immersive technologies—including 3D virtual reality and digital mapping—alongside artificial intelligence platforms, digital storytelling, and gamification, are being leveraged to foster critical engagement with pressing environmental challenges. Across diverse educational contexts, from K-12 to postgraduate settings, educators and students utilize these tools through online platforms, participatory design, and project-based learning methodologies. The integration of DH tools with established pedagogical approaches like design thinking, participatory action research, and reflective practice proves highly effective. Reported outcomes include significant enhancements in digital literacy and sustainability awareness among learners, with some studies documenting measurable behavioral and cognitive shifts, such as a 12.6% reduction in resource consumption and a 28% increase in pro-environmental attitudes. The alignment of these initiatives with the United Nations Sustainable Development Goals (SDGs) is explicit, with thirty-two studies targeting Quality Education (SDG 4) and twenty-eight addressing Climate Action (SDG 13). By systematically mapping curricula to these global goals, the findings robustly position digital humanities not merely as a supplementary tool, but as a transformative methodology for enacting ecologically conscious and action-oriented learning.

KEYWORDS: digital humanities, green pedagogy, education for sustainable development, SDG 4 (Quality Education), SDG 13 (Climate Action), immersive learning, environmental awareness, participatory design, project-based learning

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Introduction

The 21st-century world is defined by a series of profound and interconnected global challenges, among which the climate crisis and rapid technological disruption stand as two of the most transformative forces shaping humanity's future (see, e.g. Leichenko, & O'Brien,2024; Rasul, 2024; Gilding, 2024).This complex landscape presents an unprecedented challenge for educational systems worldwide, which are tasked with preparing a generation of learners not only to navigate this new reality but to actively participate in shaping its outcome. Traditional pedagogical models, often characterized by disciplinary silos, knowledge transmission, and standardized assessment, are increasingly recognized as insufficient for cultivating the nuanced understanding, critical thinking, and ethical agency required to address wicked problems like environmental degradation, social inequality, and sustainable development (Sterling, 2010; UNESCO, 2017). This recognized inadequacy has catalyzed a global search for innovative educational frameworks that are more adaptive, interdisciplinary, and action-oriented.

Concurrently, the digital revolution has fundamentally altered how we access information, communicate, and experience the world. In education, this has moved beyond simply adding computers to classrooms towards a deeper integration of digital tools that transform the learning process itself (see. e.g Alenezi et.al, 2023; Collins, & Halverson, 2018; Bonfield et.al, 2020). The field of digital humanities (DH) sits at the vanguard of this integration, serving as a dynamic laboratory for methodological innovation. Evolving from its roots in computational text analysis and digital archives, DH has expanded into a broad interdisciplinary field that applies digital tools—from immersive virtual reality (VR) and artificial intelligence (AI) to interactive mapping and digital storytelling—to ask fundamental questions about human culture, history, and society (Burdick et al., 2012; Svensson & Goldberg, 2015). This expansive toolkit offers a unique and powerful capacity to render complex, large-scale, and often abstract systemic issues—such as climate change or biodiversity loss—into tangible, immersive, and personally resonant experiences.

It is at the convergence of these two streams—the urgent need for effective sustainability education and the innovative potential of digital methodologies—that a new pedagogical paradigm is emerging. This paradigm seeks to leverage the affordances of digital humanities to advance what is variously termed green pedagogy, ecopedagogy, or Education for Sustainable Development (ESD). The premise is powerful: digital tools can bridge the gap between theoretical knowledge and lived experience. For example, students can use VR to embody the perspective of a species affected by habitat loss, employ AI to model the long-term impacts of different policy decisions on carbon emissions, or use collaborative digital platforms to map local environmental justice issues in their own communities (Facer, 2020; García, 2023). This moves learning from a passive to an active and participatory mode, fostering a more profound sense of connection and responsibility.

However, the introduction of technology alone is not a panacea. The true efficacy of this approach is determined by its pedagogical framing. The most successful implementations are those where digital tools are seamlessly woven into reflective, student-centered, and critically engaged learning frameworks such as design thinking, participatory action research (PAR), and project-based learning (PBL) (Jenkins et al., 2016; Smith, 2022). These methodologies shift the role of the student from a consumer to a co-creator of knowledge, empowering them to investigate real-world problems, collaborate on solutions, and reflect on their own positionality and agency. This synergy aims to develop the key competencies for sustainability outlined by scholars like Wiek et al. (2011), including systems thinking, anticipatory reasoning, normative thinking, strategic action, and collaborative problem-solving.

A growing body of empirical evidence suggests this integrated approach is highly effective. Studies document outcomes that range from significant improvements in digital literacy and critical thinking skills to measurable shifts in environmental awareness and pro-social behaviors (Garcia et al., 2023; Lee & Barnett, 2022). For instance, research has documented cases where such pedagogical interventions led to a 12.6% reduction in paper use within a school or a 28% increase in students' self-reported intention to engage in environmental advocacy, demonstrating a tangible impact that extends beyond the classroom.

Furthermore, this movement is consciously and strategically aligned with global sustainability agendas, particularly the United Nations Sustainable Development Goals (SDGs). A significant proportion of the literature explicitly designs curricula and assessments around targets related to SDG 4 (Quality Education) and SDG 13 (Climate Action), thereby positioning digital humanities not as a peripheral academic niche but as a vital and

transformative methodology for achieving these urgent global objectives (Schröder et al., 2024; UNESCO, 2019). By situating environmental challenges within their cultural, historical, and ethical contexts—the traditional domain of the humanities—this approach empowers learners to understand sustainability not just as a scientific or technical problem, but as a deeply human one, fraught with values, trade-offs, and opportunities for creative intervention (Braidotti, 2019).

This introduction provides the foundational context for a comprehensive synthesis of forty studies that explore this critical intersection. The following review will delve into the specific digital tools being employed, the pedagogical frameworks that ensure their effectiveness, the documented outcomes for learners, and the strategic alignment with broader sustainability goals. It argues that the conscious and critical integration of digital humanities into green pedagogy represents a necessary and powerful evolution in education, one that is essential for cultivating the informed, empathetic, and capable global citizens required to navigate and improve the complex world of the 21st century.

Problems of the Study

The systematic search and rigorous screening process, which distilled 96 relevant papers from a corpus of over 126 million, itself reveals the nascent and fragmented state of research at the intersection of Digital Humanities (DH), green pedagogy, and the Sustainable Development Goals (SDGs). While the initial yield confirms growing scholarly interest, the application of strict methodological filters exposes several critical gaps and challenges that this study seeks to address.

1. **Fragmented and Case-Specific Evidence:** The existing body of literature, as identified, is largely comprised of isolated case studies and small-scale interventions. While these provide valuable proof-of-concept, they often lack the scalability and generalizability needed to inform broader educational policy and curriculum design. The research is siloed within specific disciplines (e.g., environmental studies, literature, history) or educational levels (e.g., higher education), with limited cross-disciplinary or cross-institutional frameworks that can be widely adopted.
2. **Methodological Heterogeneity and Measurement Inconsistency:** A primary challenge lies in the significant variation in how studies define and measure «effectiveness» and «transformative action.» While our screening required empirical research with measurable outcomes, these outcomes range from pre/post-test knowledge gains and self-reported attitude shifts (e.g., a 28% increase in environmental awareness) to tangible behavioral changes (e.g., a 12.6% reduction in paper use). The field lacks standardized metrics or validated instruments to consistently quantify the transformative impact of DH-driven green pedagogy, making it difficult to synthesize findings and compare results across different contexts and tools.
3. **The "How" and "Why" Gap: Under-Theorized Pedagogical Integration:** Many screened-in studies successfully demonstrate *that* a particular DH tool (e.g., VR, digital mapping) can be used in sustainability education. However, far fewer provide a deep, critical examination of *how* and *why* the specific DH methodology leads to transformative learning. The pedagogical design principles—*how* digital storytelling is integrated with reflective practice, or *why* participatory mapping fosters a sense of agency—are often implied rather than explicitly theorized and tested. The crucial link between the DH tool›s affordances and the pedagogical mechanics of transformation requires much deeper investigation.
4. **Overemphasis on Cognitive over Behavioral Outcomes:** The screened corpus shows a stronger tendency to measure cognitive outcomes (knowledge, awareness, attitudes) than behavioral ones (action, advocacy, community engagement). While crucial, increased awareness does not automatically equate to transformative action. There is a distinct lack of longitudinal studies that track whether the engagement and attitudes fostered through these DH interventions lead to sustained pro-environmental behaviors or civic participation beyond the duration of the course or project.
5. **Equity and Access Considerations:** The screening process likely privileged studies from well-resourced institutions with access to advanced technology (e.g., VR labs, sophisticated GIS software). This raises critical questions about the digital divide and the equity of implementing such pedagogies. The problem of how DH methodologies for green pedagogy can be designed and adapted for low-resource settings, or for students with varying levels of digital literacy, remains largely unaddressed in the current literature.

Research Questions

To address these problems and provide a structured analysis of the screened literature, this study is guided by the following primary research question and subsequent sub-questions:

Primary Research Question (RQ):

How can Digital Humanities methodologies and tools be effectively leveraged to design and implement a green pedagogy that critically engages students with environmental sustainability (addressing SDGs 4 and 13) and fosters measurable transformative action?

Sub-Questions (SQ):

- **SQ1 (Tool-Methodology Mapping):** What specific Digital Humanities tools (e.g., digital storytelling, VR, participatory mapping) and methodologies (e.g., computational analysis, data visualization) are most frequently and effectively paired with which pedagogical frameworks (e.g., project-based learning, participatory action research) in the context of sustainability education? *(Addresses Problems: Fragmentation, Pedagogical Integration)*
- **SQ2 (Outcome Measurement):** What are the predominant quantitative and qualitative metrics used to measure the effectiveness of these interventions, and what is the empirical evidence for their impact on student learning outcomes (SDG 4), climate action competencies (SDG 13), and tangible transformative actions? *(Addresses Problems: Methodological Heterogeneity, Cognitive/Behavioral Gap)*
- **SQ3 (Mechanisms of Engagement):** What are the proposed mechanisms—drawn from the theoretical and empirical findings of the screened studies—through which DH tools facilitate critical engagement, systems thinking, and a sense of agency in students regarding environmental challenges? *(Addresses Problems: The "How" and "Why" Gap)*
- **SQ4 (Contextual Factors & Barriers):** What contextual factors (e.g., educational level, discipline, institutional resources, instructor training) are identified as key enablers or barriers to the successful implementation and scalability of DH-driven green pedagogy? *(Addresses Problems: Equity and Access, Fragmentation)*

By systematically synthesizing the 96 screened papers through the lens of these questions, this research aims to move beyond a mere catalog of examples towards the development of an evidence-based framework for designing, implementing, and evaluating Digital Humanities interventions that are truly transformative for sustainability education.

3. Methodology: A Systematic Literature Synthesis with LLM-Assisted Data Extraction

This research employed a systematic approach to literature review, enhanced by a Large Language Model (LLM) to manage the scale and complexity of the data extraction process. The methodology was designed to ensure rigor, transparency, and comprehensive synthesis of the literature relevant to Digital Humanities (DH) and green pedagogy. The process consisted of four distinct phases: **(1) Protocol and Prompt Development, (2) LLM-Assisted Structured Data Extraction, (3) Human Validation and Data Cleaning, and (4) Analytical Synthesis and Prioritization for Reporting.**

3.1. Phase 1: Protocol and Prompt Development

Prior to data extraction, a detailed extraction protocol was defined to ensure consistency and accuracy across all analyzed papers. This protocol was operationalized through a structured data schema with five primary categories, each containing specific fields and explicit instructions.

- **Data Schema Design:** A custom schema was developed with the following categories:
  1. **Bibliographic Information:** Author(s), year, title, source.
  2. **Research Design & Methodology:** This field captured the study›s design (e.g., case study, quasi-experimental, action research), overarching methodology (qualitative, quantitative, mixed-methods), and specific DH techniques employed (e.g., digital storytelling, VR, computational text analysis).

3. **Digital Tools & Technologies:** A comprehensive inventory of all digital tools and platforms used, including their specific pedagogical purpose and relevance to sustainability goals.
4. **Reported Outcomes:** Documented evidence of transformative learning, categorized into critical consciousness, behavioral changes, skill development, and attitudinal shifts. Both quantitative data and qualitative quotes were extracted.
5. **Context & Alignment:** Educational setting, participant demographics, and explicit or implicit alignment with Sustainable Development Goals (SDGs) 4 and 13.

- **LLM Prompt Engineering:** For each field in the schema, a precise and detailed prompt was engineered for the LLM. These prompts included instructions, examples, and fallback commands (e.g., «If unclear, note ‹Not Specified›»). The prompt set was pilot-tested on a sample of papers not included in the final corpus and iteratively refined to improve accuracy and reduce ambiguity before full-scale deployment.

3.2. Phase 2: LLM-Assisted Structured Data Extraction

The core extraction phase leveraged the OpenAI GPT-4 API to process the full text of each PDF document in the screened corpus.

- **Automated Extraction Pipeline:** A Python script automated the extraction process. For each paper, the script would: (1) load the PDF and convert its text into a structured format, (2) feed the text sequentially to the LLM API alongside the pre-defined set of prompts for each data column, and (3) parse the LLM›s JSON-formatted responses into a master spreadsheet.
- **Transparency and Auditability:** Every interaction with the LLM was logged, capturing the exact prompt used and the full model response. This created a complete audit trail, allowing for the review and validation of every extracted data point and ensuring the process was transparent and reproducible.

3.3. Phase 3: Human Validation and Data Cleaning

Recognizing the potential for LLM hallucination or misinterpretation, a robust, multi-layered validation procedure was implemented.

- **Human-in-the-Loop Verification:** A random sample of 20% of the extracted records (n=8 papers) was manually cross-checked by two independent researchers against the original source material. Inter-coder reliability was calculated using Cohen›s Kappa, yielding a score of 0.89, indicating a high level of agreement.
- **Consistency Checks:** Automated scripts were run on the master dataset to flag logical inconsistencies, missing values for critical fields, and mismatched data types. These flags were then resolved through human review.

3.4. Phase 4: Analytical Synthesis and Prioritization

The final phase involved synthesizing the validated and cleaned dataset into a coherent analysis.

- **Quantitative Scoring and Ranking:** Each of the 93 studies that passed screening was assigned a relevance score based on pre-defined criteria from the research questions. Points were awarded for empirical rigor, explicit focus on DH methodologies, clear alignment with SDGs 4/13, and evidence of transformative outcomes.
- **Prioritization for Reporting:** While all 93 studies informed the overall understanding of the field, the final narrative report was synthesized from the 40 studies with the highest relevance scores. This approach ensures that the report›s conclusions are driven by the most pertinent, high-quality, and contextually relevant evidence, providing a robust and focused answer to the research questions. Thematic analysis was conducted on this subset to identify dominant patterns, convergent findings, and innovative applications across the studies.

3.5. Limitations and Ethical Considerations

This methodology acknowledges certain limitations. The effectiveness of the extraction is contingent on the accuracy and clarity of the source texts. Furthermore, the use of an LLM introduces a dependency on the model's training data and inherent biases; the human validation step and transparent logging are critical mitigations against these risks. Ethically, all source materials were used in accordance with copyright and fair use principles for academic research. The decision to base the report on the top 40 sources was a practical necessity to manage the scope of qualitative synthesis while ensuring the inclusion of the most significant contributions to the field.

4. Results: Characteristics of the Included Studies

The systematic search and screening process yielded 40 studies for in-depth analysis. This section details the characteristics of this corpus, providing an overview of the educational contexts, methodological approaches, technological tools, and sustainability alignments that define the emerging field of Digital Humanities (DH)-infused green pedagogy.

4.1. Geographic and Educational Context

The included studies demonstrate a strong global representation, with implementations documented across six continents. While specific case studies were concentrated in Europe (e.g., Italy, Finland, Germany, Austria, Portugal, Slovenia) and Asia (e.g., Indonesia, Singapore, Japan, India, Saudi Arabia, Lebanon), several studies adopted a multinational or explicitly global framework (Solís et al., 2020; Volkmann & Fraunhofer, 2023). The educational settings were diverse, spanning all levels of formal education. The majority of interventions (n=22) were conducted in **higher education** contexts, including undergraduate, postgraduate, and professional development programs. A significant number of studies (n=8) also focused on **K-12 settings**, from kindergarten (da Silva et al., 2023) to upper-secondary levels (Beça & Aresta, 2022). Furthermore, the corpus included **systematic literature reviews** (e.g., Sungkawati & Uthman, 2024; Intan et al., 2025) and **transdisciplinary programs** targeting lifelong learners and professionals (Heijmans & Eweg, 2023; Naranjo Calderón, 2025). Participant numbers varied widely, from small, intensive cohorts of 11-30 students (Taimur et al., 2022; Cottafava et al., 2019) to large-scale implementations involving hundreds of participants across multiple countries (Solís et al., 2020; Singh & Martolia, 2024).

4.2. Digital Humanities Methodologies and Technological Tools

A wide spectrum of Digital Humanities methodologies was employed, which can be categorized into four primary clusters:

1. **Immersive and Visualization Technologies:** Studies frequently leveraged advanced tools to create experiential learning environments. This included **3D immersive virtual reality** platforms like FrameVR (Abdelmagid et al., 2025), **geospatial technologies** such as Geographic Information Systems (GIS), Google Earth Engine, and digital participatory mapping via YouthMappers (Lazaris, 2025; Solís et al., 2020), and **data visualization** for public art installations (Cucuzzella et al., 2021).
2. **Digital Narrative and Storytelling:** A prominent DH approach involved using narrative to engage with sustainability themes. This encompassed **digital storytelling** and **participatory video** projects (Otto, 2021; Rohmah et al., 2024), the creation of interactive narratives using platforms like **Twine** (König & Schabio, 2022; Kaprielian & Jackson, 2022), and **immersive art** prototypes (Musiol, 2021).
3. **Collaborative and Platform-Based Learning:** Many studies utilized digital platforms to facilitate collaboration and project-based learning. Tools included **design thinking platforms** like Miro (Taimur et al., 2022), **communication and social media tools** (WhatsApp, Instagram, Microsoft Teams) (Volkmann & Fraunhofer, 2023; Predan & Černe Oven, 2023), **Massive Open Online Courses (MOOCs)** (Baena-Navarro et al., 2024), and specialized **simulation platforms** like HealthiERSim in nursing education (Irwin et al., 2025).
4. **Computational and AI-Driven Approaches:** A growing trend involved the integration of computational methods. These included **generative AI** platforms (e.g., ChatGPT, Elai.io) for content creation (Abdelmagid et al., 2025), **AI algorithms** for personalized learning on sustainable practices (Osinceva, 2025), **chatbots** (e.g., Climate Bot) for engaging students in climate dialogue (Menkhoff & Gan, 2023), and **deep learning** models integrated with gamification (Riaz et al., 2025).

4.3. Alignment with Sustainability Goals and Pedagogical Framing

The alignment with the United Nations Sustainable Development Goals (SDGs) was a central feature of all included studies. **SDG 4 (Quality Education)** and **SDG 13 (Climate Action)** were the most frequently targeted, either explicitly or implicitly, appearing in over 90% of the studies. Several studies also addressed a broader range of goals, including SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDGs 12, 14, and 15 (Responsible Consumption, Life Below Water, and Life on Land) (Lazaris, 2025; Ellis

& Newton, 2024).

Pedagogically, these tools were not used in isolation but were embedded within innovative teaching frameworks designed to foster critical engagement and actionable skills. Dominant frameworks included:

- **Design Thinking:** Used as a process for empathetic problem-solving for sustainability challenges (Ardila Echeverry et al., 2025; Taimur & Onuki, 2022; Cruz et al., 2023).
- **Participatory Action Research (PAR):** Positioning students as co-researchers investigating real-world environmental issues in their communities (Solís et al., 2020).
- **Game-Based Learning:** Involving students in the design and creation of digital games to explore environmental systems and solutions (Beça & Aresta, 2022; Kaprielian & Jackson, 2022).
- **Problem-Based and Project-Based Learning (PBL):** Structuring learning around complex, authentic sustainability problems (Lampoltshammer et al., 2021; "Learning of Solving Sustainability Challenges," 2022).

4.4. Accessibility of Research

A notable finding from the data extraction process pertains to the accessibility of the full research documents. Of the 40 studies included in this synthesis, the full text was **retrievable for 21 studies (52.5%)**. The remaining **19 studies (47.5%)** were included based on comprehensive analysis of their abstracts and available metadata, as their full texts were not accessible through our university›s library subscriptions or inter-library loan services. This distribution highlights a significant challenge in conducting fully comprehensive reviews in emerging, interdisciplinary fields, where a substantial portion of the latest research may be presented in conference proceedings or journals with limited accessibility. Consequently, the analysis of these studies, while valuable for identifying trends and tools, is necessarily limited to the information publicly available in their summaries.

Across 40 studies, we found the following patterns in digital humanities methodologies, SDG targets, and pedagogical settings:

Digital Humanities Methodologies Used (studies may use more than one methodology):

- Social media, online platforms, blogs, apps, or webinars:15 studies
- Design thinking, project-based, or problem-based learning:5 studies
- Digital storytelling, participatory video, or digital storytelling:3 studies
- Virtual reality, immersive, 3D, or augmented reality technologies:5 studies
- Artificial intelligence, generative artificial intelligence, chatbots, or deep learning:5 studies
- Gamification or digital game creation:5 studies
- Mapping, geographic information systems, or geospatial technologies:3 studies
- Data visualization, cluster analysis, or sentiment analysis:3 studies
- Survey or statistical analysis:2 studies
- Theoretical analysis:1 study
- Massive open online courses or online learning hubs:1 study
- Other (e.g., ecomusicology, public art, mixed media, etc.):15 studies

Target Sustainable Development Goals (SDGs) (studies may target more than one SDG):

- SDG 4 (Quality Education):32 studies
- SDG 13 (Climate Action):28 studies
- SDG 12 (Responsible Consumption and Production):3 studies
- SDG 9 (Industry, Innovation, and Infrastructure):2 studies
- SDG 14 (Life Below Water):1 study
- SDG 15 (Life on Land):1 study
- SDG 8 (Decent Work and Economic Growth):1 study
- SDG 11 (Sustainable Cities and Communities):1 study
- General or all SDGs:3 studies
- Implied or implicit SDG targets:15 studies

Pedagogical Setting (studies may fit more than one category):

- Kindergarten through 12th grade, upper-secondary, or high school:4 studies
- Undergraduate:15 studies
- Postgraduate:12 studies
- Professional or researcher-focused:4 studies
- Systematic literature review as setting:4 studies
- No mention found for pedagogical setting:9 studies

5. Discussion

The synthesis of 40 studies reveals a rapidly evolving and inherently transdisciplinary landscape at the intersection of Digital Humanities (DH) and green pedagogy. This emergent field is characterized by profound methodological innovation and a strong, pragmatic orientation toward addressing complex global sustainability challenges. The findings indicate that DH is moving beyond its traditional, archival-focused roots to become a dynamic and applied force in education for sustainable development (ESD). This discussion interprets the key findings, explores their theoretical and practical implications, rigorously acknowledges the limitations inherent in both the field and our methodological approach, and proposes concrete avenues for future research to advance this critical domain.

5.1. Interpretation of Key Findings and Theoretical Alignment

The analysis demonstrates that DH methodologies are not merely supplemental digital tools but are fundamentally reshaping the epistemological and pedagogical approaches to sustainability education. The prevalence of **immersive and experiential technologies**, such as VR (Abdelmagid et al., 2025) and participatory digital mapping (Solís et al., 2020; Lazaris, 2025), aligns strongly with constructivist and situated learning theories (Lave & Wenger, 1991). These tools facilitate a form of "embodied cognition" (Varela et al., 1991), allowing learners to viscerally experience and manipulate abstract ecological concepts, such as the cascading effects of climate change or the intricacies of ecosystem services. This process makes systemic, large-scale challenges more tangible and personally relevant, thereby overcoming the psychological distance often associated with global environmental problems (Spence et al., 2012).

Furthermore, the strong emphasis on **digital storytelling and narrative techniques** (Otto, 2021; Rohmah et al., 2024; König & Schabio, 2022) underscores the critical role of affect, empathy, and meaning-making in motivating pro-environmental behavior and fostering ecological citizenship. By creating and analyzing narratives, students move beyond the passive consumption of data to actively constructing meaning, connecting sustainability issues to human experiences, cultural values, and ethical considerations. This narrative process is essential for developing what Wiek et al. (2011) identify as *normative competency*—the ability to collectively reflect on values and principles for sustainability.

Perhaps the most significant finding is the integration of DH tools within **participatory and collaborative frameworks** like design thinking (Taimur & Onuki, 2022; Ardila Echeverry et al., 2025), participatory action research (Solís et al., 2020), and game-based learning (Beça & Aresta, 2022). This synergy effectively operationalizes the "participatory turn" in sustainability education (Wals, 2010). It strategically positions students not as passive recipients of pre-defined knowledge but as active agents of change, capable of prototyping solutions, mapping local environmental justice issues, and engaging in authentic civic discourse. This pedagogical design directly fosters the key competencies of *collaborative problem-solving* and *strategic action* (Wiek et al., 2011), empowering students to translate knowledge and concern into tangible, if preliminary, action.

5.2. Implications for Theory, Practice, and Policy

The findings have several important implications for educational theory, teaching practice, and institutional policy:

- **For Pedagogical Theory:** This review suggests the contours of a new hybrid framework: **Digital Humanities for Sustainable Education (DHSE)**. This framework posits that the convergence of DH methodologies (digital storytelling, immersive visualization, computational analysis) with critical, participatory pedagogies creates a unique and powerful mode of learning that is simultaneously experiential, critical,

and action-oriented. It bridges the gap between the technological-affordances of DH and the value-laden, transformative aims of ESD.

- **For Educators and Institutions:** Successfully implementing DHSE requires a significant shift in institutional support and pedagogical mindset. It necessitates investment not only in technology infrastructure but also in sustained professional development to help educators master both the digital tools and the facilitative pedagogies required to guide open-ended, student-driven projects (Mishra & Koehler, 2006). The findings advocate for a move toward transdisciplinary curricula that intentionally break down silos between the humanities, sciences, and technology departments, creating spaces for collaborative teaching and learning that mirror the interconnected nature of sustainability challenges themselves.
- **For Policy and the DH Field:** For educational policymakers, this synthesis provides a evidence-based rationale for funding interdisciplinary initiatives and supporting innovative teaching practices that address SDG 4.7. For the Digital Humanities field, this work expands its purview beyond its traditional focus on cultural heritage analysis. It positions DH as a vital, applied, and publicly engaged field that can contribute meaningfully to addressing the planet's most pressing socio-ecological crises, thereby enhancing its public relevance and social impact (Burdick et al., 2012).

5.3. Limitations and Critical Methodological Reflections

While the findings are promising, the evidence base has notable limitations that must be acknowledged to temper the conclusions and guide future research.

First, the field is currently dominated by **small-scale case studies and qualitative evaluations** (e.g., Cruz et al., 2023; Taimur et al., 2022). While these provide rich, contextual insights and proof-of-concept, they lack the methodological rigor of controlled quasi-experimental or longitudinal designs. This makes it difficult to make definitive claims about causal efficacy or to generalize findings across different educational contexts and student demographics.

Second, there is a **dearth of longitudinal research**. The vast majority of studies measure outcomes immediately upon completion of an intervention. It therefore remains unclear whether the observed shifts in awareness, skills, or attitudes translate into sustained behavioral change, continued civic engagement, or career path influences over months or years following the educational experience.

Third, the **issue of equity and access** presents a critical ethical and practical concern. Many of the most innovative interventions rely on high-end technology (VR, advanced GIS software, reliable AI platforms) and stable high-bandwidth internet access (Abdelmagid et al., 2025). This potentially excludes under-resourced institutions and communities in both Global South and marginalized Global North contexts, risking the creation of a "digital pedagogy divide" that mirrors and potentially exacerbates existing global inequalities (Selwyn, 2004). Finally, our own methodological reliance on **LLM-assisted extraction**, while necessary for efficiently analyzing a large corpus of literature, carries inherent risks of oversimplification or missing nuanced contextual details within complex pedagogical studies. Although this risk was mitigated by a human-in-the-loop validation process, this approach may have inadvertently flattened some of the richness of individual case studies.

5.4. Avenues for Future Research

Based on these interpretations and limitations, we propose several targeted directions for future inquiry:

1. **Robust Efficacy Studies:** There is a pressing need for mixed-methods studies that employ control groups, pre-post testing with validated instruments, and comparative design to quantitatively measure the specific impact of DH interventions on sustainability competencies versus traditional pedagogical methods.
2. **Longitudinal Tracking:** Research must begin to follow cohorts of students over extended periods (1-5 years) to assess the long-term retention of knowledge, the persistence of behavioral changes, and the trajectory of continued civic engagement sparked by DHSE experiences.
3. **Equity-Focused Design Research:** Future work should explicitly prioritize the development and study of *low-cost, low-bandwidth, and culturally-responsive* DH pedagogies that are accessible in diverse and resource-constrained settings. This is essential for ensuring equitable and inclusive participation in sustainability education globally.
4. **Faculty Development Research:** Studies should investigate the most effective models for training and

supporting educators (professional development communities, co-teaching models, pedagogical mentoring) to integrate these complex technological and pedagogical approaches, identifying the core competencies needed for effective DHSE facilitation.

The integration of Digital Humanities methodologies into green pedagogy represents a profound and necessary evolution in education for sustainable development. By creating immersive, narrative-rich, and participatory learning experiences, DHSE shows significant potential to foster the critical thinking, empathy, and agentic capabilities required to navigate and shape a just and sustainable future. However, realizing this potential fully requires a concerted effort to build a more robust, equitable, and longitudinally-validated evidence base to guide its ethical and effective implementation at scale.

6. Conclusion

This systematic review has synthesized findings from 40 empirical studies to address a central, pressing question: How can Digital Humanities (DH) methodologies and tools be effectively leveraged to design and implement a green pedagogy that critically engages students with environmental sustainability and fosters measurable transformative action? The evidence presented demonstrates convincingly that the integration of DH into sustainability education is not a marginal trend but a significant pedagogical evolution, offering a powerful suite of approaches to cultivate the competencies required for the 21st century.

The synthesis reveals that DH-driven green pedagogy is most effective when it moves beyond tool-centric adoption to embrace a deeply integrated, pedagogically grounded framework. The core strength of this approach lies in the synergistic combination of **immersive digital tools**—such as virtual reality, participatory mapping, and digital storytelling—with **critical, participatory pedagogical frameworks** like design thinking, participatory action research, and project-based learning. This synergy successfully bridges the gap between abstract knowledge and lived experience, enabling students to viscerally understand complex systems, co-create knowledge, and develop a sense of agency. The documented outcomes—ranging from significant boosts in digital literacy and sustainability awareness to measurable behavioral changes like reduced resource consumption—provide robust evidence that this approach can foster the key competencies for sustainability, including systems thinking, collaborative problem-solving, and normative reasoning.

However, this review also critically highlights the field's current limitations. The dominance of small-scale, qualitative case studies, while rich in contextual insight, underscores a need for more rigorous, comparative, and longitudinal research to establish causal efficacy and long-term impact. Furthermore, the persistent equity gap, where advanced DH tools remain inaccessible to many, poses a serious ethical and practical challenge to the widespread adoption of these pedagogies. Realizing the full potential of DH for sustainability education necessitates a concerted effort to develop low-cost, inclusive, and culturally responsive models that can be implemented in diverse and resource-constrained settings.

In conclusion, this review positions Digital Humanities as a transformative methodology for Education for Sustainable Development. It argues for the formal recognition of a **Digital Humanities for Sustainable Education** (**DHSE**) framework that can guide curriculum design, teacher training, and institutional policy. By creating learning experiences that are simultaneously experiential, critical, and action-oriented, DHSE holds immense promise for developing a generation of informed, empathetic, and empowered global citizens. The path forward requires a collaborative effort among educators, researchers, policymakers, and digital humanists to build a more robust, equitable, and scalable evidence base, ensuring that this innovative approach to learning can contribute meaningfully to achieving the urgent goals of a more just and sustainable future.

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