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Unsustainability in Sustainability Education: Limits of Technology In Situ

Alessandro Pollini * and **Gian Andrea Giacobone**

Faculty of Psychology, Uninettuno Telematic International University, 00186 Rome, Italy; gianandrea.giacobone@uninettunouniversity.net
* Correspondence: alessandro.pollini@uninettunouniversity.net

Abstract

This study examines the challenges of implementing educational technologies for sustainability education in diverse, real-world settings. While such tools are often designed for universal applications, a multitude of contextual factors, particularly in low-resource scenarios, can impede their full implementation. Through a series of in situ experiments conducted across three educational settings in Greece, Romania, and Italy, the research revealed that field deployment yields critical insights into organisational and technical limitations that are not evident in controlled experiments. The key findings underscore the importance of incorporating a broad range of socio-technical factors into design research protocols. The research also reveals a significant trade-off between the readiness of a tool and the need for its contextualisation, underscoring that effective implementation requires iterative adaptation and tailored training. Ultimately, the work concludes that real-world deployment blurs the distinction between a prototype and a product, necessitating a flexible approach to ensure equitable and prosperous adoption.

Keywords: sustainability education; sustainable interaction design; design ethnography

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1. Introduction

Technology-enhanced education offers society a substantial modernisation of teaching methods, learning approaches, communication, interaction, and access to and exchange of information among teachers, students, and scientific researchers [1]. Rapid advances in the field of computing and information and communications technologies (ICTs) are providing new, engaging, interactive and customised technology-focused learning experiences that stimulate motivation [2], adopt a constructivist context of training, and multi-modal and multi-sensory forms of interaction to foster active and mobile learning [3–6] through new advanced technologies [7,8] and digital games [9,10].

Despite these advancements, the implementation of technology-enhanced education faces significant obstacles, particularly in resource-constrained environments. The diverse needs of student populations and the varying allocation of financial, in-kind, physical, and human resources present critical challenges [11]. Contemporary global phenomena, including demographic shifts, migration, and rising inequalities, have intensified the diversity within educational communities and classrooms, exposing significant disparities in access to digital technologies and the internet. A primary concern is that new digital technologies and ICTs are often designed without adequate consideration for the diverse requirements of teachers and students, especially those from marginalised communities [12,13].

The oversight stems from a Western technocratic cultural bias, wherein technologists and designers operate under the implicit assumption of infinite resources and limitless potential, deploying powerful digital and cloud-based services for a user base assumed to be fully competent and aware of the technology's capabilities and impacts [14]. Such a mindset has raised new ethical questions for technology-enhanced learning, reflecting concerns in the field of Sustainable Human–Computer Interaction [15–17] and Sustainable Interaction Design (SIxD) [18–20]. In particular, criticism arose against the "cornucopian vision," which suggests an abundance of resources and continuous technological progress, neglecting its negative impact on people's well-being and the environment [21].

In this regard, the research explores the use of interactive technologies in support of education, with a focus on its contextual adaptation and response to resource limitations of three different and heterogeneous learning scenarios [22]. The activities for data collection employ an in-the-wild research methodology [23–25]. The field-based approach incorporates human-centred and participatory design techniques directly in the user's real-world setting [26,27]. The following questions guided the study:

RQ1. *To what extent do digital technologies for education meet diverse user needs and requirements?*

RQ2. *What lessons can we learn from developing technologies designed for resource-limited settings?*

We explore the field of Sustainability Education by conducting design experiments with technology-enhanced learning. Based on our findings, we discuss how the collected data contribute to an investigation of key conflicts within the discourse on sustainable technology development at four distinct levels:

- The philosophical perspective: The cornucopian view of technology implementation against the reality of limited infrastructure in real-world educational scenarios.
- The educators' perspective: Educators' preparedness versus their actual lack of green competencies.
- The artefacts' perspective: The functionalist approach to technology design, in contrast to the sustainable, inclusive, and human-centred perspective.
- The technology perspective: The expected technology readiness level of the final tool, in contrast to the actual maturity of the experimental research prototypes used in the design experiments.

The first section of the paper provides a theoretical foundation for understanding sustainable technology development through a cultural and critical theory lens. We then demonstrate how such conceptual reframing enables a more effective design-oriented engagement with sustainability education. Finally, we present three specific design experiments from different sustainability education scenarios and discuss the findings, illuminating these conflicts.

2. Designers' Commitment to Sustainability Education

The current climate crisis underscores the urgent need to raise designers' awareness and promote a sociocultural transition towards more sustainable and environmentally friendly lifestyles [28,29].

The awareness of design to assume its responsibility regarding environmental sustainability is leading to a genuine concern [30–33] within the design community today. The importance of design for ecological and social sustainability is recognised in the increasing number of conferences and workshops, like LIMITS—Computing within Limits and Post-growth HCI: Co-Envisioning HCI Beyond Economic Growth [17], design education programmes, ranging from Eco-Social Design to Sustainable Design courses, in Universities like Carnegie Mellon University, Stanford University, Edinburgh University, University of Bolzano, University of Florence, Politecnico di Torino, and many others. Such a collective effort towards environmentally conscious design fosters imagining different futures through digital and physical objects, built environments, and services that comply with the principles of social, economic, and ecological sustainability [34–36].

More specifically, design practitioners and researchers of SIxD, who advocate for fostering sustainability *-through* and *-in* design principles, practices, and results, require reframing their design abilities in low-resource scenarios and contextual constraints [37]. Specifically, designs for resource-limited conditions should address the needs of users who cannot afford the latest technological solutions, either partially or entirely [38], and prevent discrepancies between user experience and product specifications [39].

The recent study on contextual design in low-resource settings [40] categorises the most frequently mentioned contextual factors that may affect the development of technological solutions in resource-limited contexts into four main areas: individuals, physical environment, technical systems, and structures. A more recent and reframed study of the same analysis [41] differentiates and simplifies the terminology classification to address the conceptual framework specifically in the context of Sustainability Education.

The new structure divides the low-resource factors into three macro environments that can help designers define a resource-limited context [42]:

1. Technical factors such as device readiness, software compatibility, energy consumption, usability, and affordability;
2. Human factors, such as digital literacy, green competencies, abstraction, abilities, affective engagement, and sharing of habits and practices;
3. Physical or natural environment, including time availability, available spaces, rooms, outdoor settings, electricity availability, bandwidth, and hardware.

This structure has been adopted in the research, guiding the definition of an observation grid for observing and analysing the field experiments (explained in Section 5).

3. Materials and Methods

The urgent need for effective sustainability education in the face of the current climate crisis presents a significant methodological challenge for technologists, designers, and educators. To address this issue, an interdisciplinary research approach that integrates diverse fields is necessary. This study adopts a multidisciplinary design ethnography approach, combining engineering, software service implementation, pedagogy, and interaction design with exploratory and qualitative methods. The consequence of such synthesis is a mixed-method framework for data collection, crucial for conducting field experiments that investigate emergent conditions, contextual variations, and the "actual differentiation" [43] without imposing predetermined explanations given by design researchers.

To reach this goal, the research combines co-design workshops and in situ experiments (see Section 4) within a case-based analysis framework (see Section 3.1). The case-based analysis used three pre-designed experimental research prototypes (see Section 3.2), each incorporated into separate experimental studies, to explore the contextual implications of their implementation and adaptation in resource-limited learning environments.

To evaluate the effectiveness of technology-enhanced learning in resource-constrained settings, the authors developed a four-stage task analysis protocol (see Section 3.3). This protocol aimed to support the development of targeted learning experiences linked to pre-designed educational technologies across three case studies, while also collecting qualitative data on contextual factors that influenced the full and optimal use of the intended digital tools in resource-limited educational settings.

3.1. Case-Based Analysis

The authors employed a case-based analysis to investigate experimental research prototypes across three contexts, utilising a qualitative research approach that examines complex phenomena in their real-life contexts. Rather than aiming for broad generalisation, this method seeks to generate deep, contextualised insights by examining cases as bounded yet dynamic units of analysis [44–46].

To ensure rigour, the cases employ multiple sources of data—such as interviews, field observations, and documents—and thus enable triangulation, enhancing the validity of the data collection [47,48]. Analytical procedures often draw on qualitative content analysis and multi-stage interpretive frameworks [49,50], which support systematic coding and theorisation. In this way, case-based analysis not only facilitates a nuanced understanding of situated practices and experiences but also contributes to methodological and theoretical advancement across disciplines. In-the-wild design ethnography [51] has been adopted for data collection about new technologies and experiences in situ [52], unlike user-centred approaches, which typically begin by observing existing practices and then suggesting general design implications or system requirements.

Regarding this specific study, the case-based analysis involves three experimental and participatory research studies conducted across three educational institutions in three European countries (Greece, Italy, Romania) from Spring 2022 to Winter 2024 (explained in detail in Section 5).

The research activities involved a heterogeneous group of participants, comprising educational managers, educators, and students. The study aimed to address specific questions: *How can we enhance the educational value of digital devices and services to promote sustainability education and mitigate social and environmental issues? What do educators and students perceive as meaningful in the context of learning through the interaction of this technology, and how can we guarantee the effective and long-term utilisation of it in its intended context?*

These three workshops: (1) explored a broader understanding of users' experiences with the proposed digital technologies, and (2) employed participatory methods to engage participants in the design process during the early phase (e.g., Sanders and Stappers in [53]) to improve technology implementation.

The activities were ethically approved by the Comisión de Ética en la Experimentación Animal y Humana (CEEAH) under the EU H2020 GreenSCENT project at the Universitat Autònoma de Barcelona. All participants provided informed consent to participate in the research activities voluntarily; in the case of minors, permission was obtained from their parents or guardians.

3.2. Interactive Prototypes

The three experimental research studies involved participants to explore the potential and implications of technology-enhanced learning solutions in sustainability education. Specifically, the investigation examined the pedagogical opportunities of three existing interactive technologies, initially created by the authors to develop sustainability competencies through interactive, collaboratively built learning experiences, by testing them in real-world settings. Participants interacted with the technologies through experimental research prototypes to identify early challenges, opportunities, and contextual implications related to their future use in resource-limited educational environments.

The experimental research prototypes under investigation included:

1. GreenVerse 360° Interactive Documentary Platform: a web-based system that enables teachers and students to create immersive 360° multimedia documentaries on sustainability topics, accessible through virtual reality.

2. Environmental Monitoring Mobile Application: a smartphone application that allows individuals to generate multimedia, geolocated reports of environmental issues and best practices within their communities.
3. CleanAir@School: a demonstrator employing passive nitrogen dioxide (NO_2) samplers as an educational tool to enhance students' understanding of air pollution by monitoring their exposure levels in urban contexts.

3.3. Protocol

Understanding a valid integration of meaningful technology-enhanced learning solutions in sustainability education and being conscious of their proper value required the formulation and experimentation of a protocol that enabled the educators to engage with educational experiences associated with pre-designed technologies.

The protocol aimed to create an experimental setting to identify contextual factors that impede the full adoption of the proposed technologies in low-resource environments, while also experimenting with new learning scenarios facilitated by technology.

The experimentation of the educational protocol aimed at creating a learning experience capable of leading students to acquire adequate literacy and pro-environmental competencies related to the eight macro areas of the Green Deal: Biodiversity, Circular Economy, Clean Energy, Climate Change, from Farm to Fork, Green Building, Smart Mobility, and Zero Pollution.

According to this assumption, the research activities established a task-specific protocol determined by four distinct tasks, which were identified as follows:

- *Task 1—Strategy and technology setup.* This phase focuses on identifying learning needs and objectives related to a specific learning domain within one of the macro areas of the Green Deal, as well as the technology used to achieve the desired educational experience. Educators and students have been acquainted with the proposed technologies, made aware of their domain scope and main features, the interaction model of commands and controls, and the possible adoption scenarios.
- *Task 2—Instructional design.* This task defines the competencies students are expected to acquire in line with the learning objectives that characterise the selected domain. Educators have been involved in a workshop-like instructional design activity to envision the practical learning experience, proposing a specific educational challenge based on the chosen technology and an evidence-based field investigation of natural phenomena.
- *Task 3—Learning format execution.* This phase establishes the entire practical educational experience and its corresponding expected outcomes, which will be conducted with the learners' active involvement. Educators and students needed to manage systematic data collection in accordance with the research scope and the available methods proposed by the selected technology.
- *Task 4—Learning evaluation.* This phase assesses the learners' learning performance by evaluating the learning outcomes developed during the educational activities proposed in the execution stage. The outcomes of the learning scenario have been assessed in relation to both the performance of participating students and the quality, appropriateness, consistency, and impact of the produced artefacts.

4. Implementation of Instructional Co-Design Workshops and In Situ Experiments

The authors gathered data from all four stages of the protocol through a combination of two distinct methods: Instructional Co-design workshops (see Section 4.1) and in situ experiments (see Section 4.2). In these activities, a consistent group of participants (see

Section 4.3) engaged in participatory design to effectively test and assess both the effectiveness of the proposed learning experiences and the technology-enhanced learning prototypes.

To provide evidence for identifying contextual factors that hinder the full implementation of proposed technologies in low-resource settings, the study structures data collection using an observation grid proposed by the authors (see Section 5). It covers multiple dimensions across the three main macro areas introduced in Section 2.

In-the-wild design ethnography methods [54], such as field experiments, prototype exploration, and contextual interviews, have been organised within and across the four stages of the task-specific protocol for data collection, as detailed below:

1. The Instructional Co-design workshop, which included prototype exploration, contextual interviews, and learning design with teachers, was adopted to carry out Tasks 1 and 2.
2. The in situ study, which involves evaluating novel research-based prototypes in various settings for specific learning activities with participants, was used to carry out Tasks 3 and 4. The in situ study was conducted using a contextual and ethnographic approach.

4.1. Instructional Co-Design Workshop

The instructional design model used to conceive and conduct the learning activities on sustainability education addresses these three main objectives:

- *Objective 1.* The acquisition of basic knowledge about Sustainability Education. Definition of Sustainability Education training needs in relation to the Green Deal objectives.
- *Objective 2.* Understanding the potential of the Greenscent framework: What the Greenscent Toolkit (materials and digital technologies) can do for green education. Definition of educational journeys, including preparatory assignment, challenge, and reporting activity.
- *Objective 3.* The definition of learning assessment methods for evaluating the effectiveness and value of the activity.

According to these primary objectives, the Instructional Co-design workshop activities are expected to produce three different outputs to create the GreenSCENT educational training kit: educational objectives and skills, educational orchestration, and assessment methods.

Each pilot study responsible for conducting the Instructional Co-design workshop received structured implementation guidelines, intended to perform activities according to the proposed educational protocol. The guidelines are based on four macro modules (Figure 1): the first two modules are related to helping educational managers and educators to define class orchestration and the learning challenge; the other two modules are explicitly dedicated to the learning activities with the students, in which the expected outcomes concerning class orchestration syllabuses and educational use cases are collected. The steps were:

1. *Sustainability Competence Domain.* Exploration and selection of a Green Deal area and suitable competences in accordance with the educators' educational objectives through the knowledge graph. Assessment of educators' skills and gap analysis in relation to specific skill cards associated with identified missing competencies.
2. *Skill cards' definition.* Explore and select specific skill cards that align with the educational objectives—in terms of Knowledge, Attitudes, and Skills—and setting educational objectives to develop new, sustainable educational activities with educators. In this regard, it is essential to determine the knowledge, skills, and attitudes students should acquire regarding sustainability.

3. *Instructional Design orchestration.* Competence acquisition is achieved by assigning tasks that require students to critically analyse sustainability issues, evaluate different perspectives, and propose innovative solutions. Orchestration thus concerns defining the educational user journey map (design for orchestration) through co-designing an educational syllabus aligned with the selected Sustainability Competence Domain and skill cards.
4. *Learning assessment.* At the end of the learning process, detailed rubrics that outline the criteria for evaluating student performance are created. Rubrics covered various dimensions, including knowledge comprehension, practical application, critical thinking, and collaborative skills [55]. The assessment included criteria that encompass cognitive, affective, and behavioural domains to capture a holistic view of student learning [56]. The evaluation was supported by the implementation of summative assessments, such as projects, presentations, portfolios, and practical exams, which enable educators to assess students' overall achievement at the end of the learning period [57].

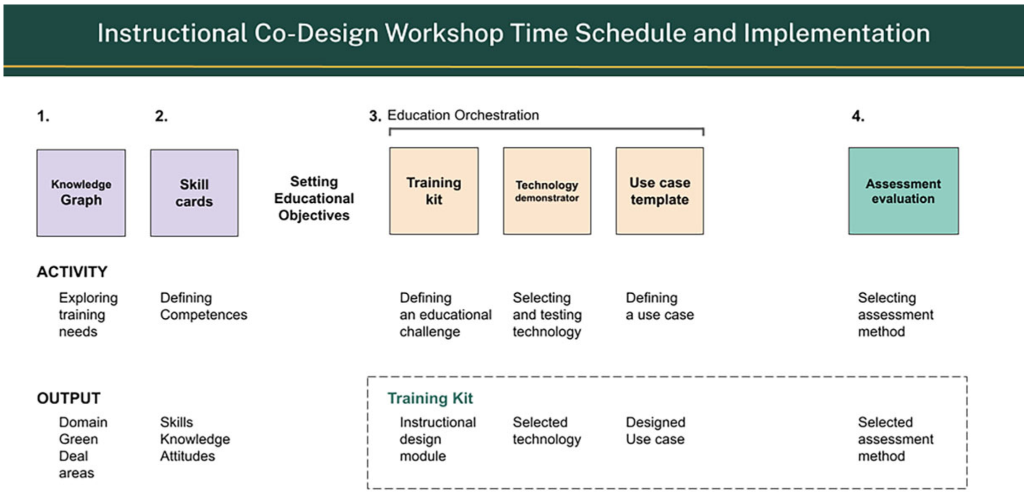

Figure 1. Implementation guidelines of the Instructional Co-design workshop activities. Source: Authors.

4.2. In Situ Studies

To investigate whether new technologies could facilitate the diving in and stepping out of the learning process, three in situ studies were conducted [58].

The in situ studies involved the contextual and situational implementation of technology-enhanced educational scenarios designed by teachers during Instructional Co-design workshops. During the studies, students were engaged by the teachers in becoming familiar with technology, collaborating in teams, and completing the educational challenges provided to them.

A significant methodological challenge was how to effectively record the learning activities of multiple students simultaneously exploring different areas of the outdoor environment and interacting with the prototypes. Such in-the-wild studies required a dynamic observation and recording solution for multiple participants moving across a large area. To address this issue, the team, composed of one facilitator and two design researchers, adopted a contextual inquiry approach. The facilitator directly interacted with participants, while the design researchers followed each team of students discreetly from a distance to observe and record their actions and conversations. This method enabled the capture of rich, qualitative data. Users' interactions with the devices were also quantitatively logged, noting the time and location of digital events and the students' subsequent responses. The educational contents produced as digital evidence, including readings, images, and audio files, were logged via the network and, whenever possible, synchronised with the observed conversations and actions.

The combination of qualitative (observations, transcripts) and quantitative (logged digital events) data was considered crucial for a comprehensive understanding of the children's learning processes within the blended indoor and outdoor environments.

4.3. Participants

This section details the total number of participants involved in the experimental and participatory design activities within the case-based analysis.

The Instructional Co-design workshops involved a total of 31 participants in three different experimental activities adopting a participatory design approach, as shown in Table 1: 8 from the first workshop in Greece (GR), 13 from the second workshop in Romania (RO), and 10 from the third workshop in Italy (IT). All three activities mainly included teachers (6 GR + 10 RO + 9 IT = 25 in total) and educational managers (2 GR + 3 RO + 1 IT = 6 in total) from secondary schools. The first workshop in Greece also included educators from primary schools, comprising three teachers.

Table 1. Participant list used in the three Instructional Co-design workshops. GR stands for Greece, RO for Romania, and It for Italy. The participants' roles are denoted ED for educational manager, T for teacher, and S for students.

#	N° Workshop	Role	Level	Participant
1	WS1-GR	ED	Secondary School	A. V.
2 3 4	WS1-GR	T	Secondary School	P. P. M. A. E. F.
5	WS1-GR	ED	Primary School	O. B.
6 7 8	WS1-GR	T	Primary School	R. A. K.S. K. C. B.
9 10 11	WS2-RO	ED	Secondary School	S. Z. M.G. A. E-A. G.
12 13 14 15 16 17 18 19 20 21	WS2-RO	T	Secondary School	N. S. L.M. S. M-M. M. E. L. R. P. L. P. D-M. A. R-M. B. O. P. L. V.
22	WS3-IT	ED	Secondary School	B.M. F.
23 24 25 26 27 28 29 30 31	WS3-IT	T	Secondary School	R. S. V. T. M.A. B. L.M. C. A. DL. V. M. C. V. S. F. R. R.

The educators involved in planning practical educational experiences in sustainability education within their academic institutions assisted the research team in recruiting students, configuring and conducting in situ studies with them, and testing the interactive prototypes.

The in situ studies involved 146 students who followed the proposed learning challenges and scenarios in an educational, real-life setting.

The Greek context involved 13 students, comprising 10 from the secondary school and 3 from the primary school. The study conducted in Romania involved 60 secondary school students. Finally, the Italian context involved four classes from the primary school, involving a total of 73 students.

5. Data Collection

Both the Instructional Co-design workshops and the in situ studies involved the design research team in field observation and note-taking to record, discuss, and interpret events and interactions with educational technologies within the given scenarios. In particular, an observation grid has been created to support field ethnography and to coordinate among observers. They were, in fact, also asked to compare their own notes with those of the other researchers to identify agreement in the interpretation of the interactions' qualities, issues, and limits.

The observation grid took into account the theoretical framework, which combines a heterogeneity of perspectives, in which the technological factor is a relevant dimension only when it relates to other contextual and situational factors associated with the different components of the socio-technical scenario. The expert perspective of design researchers enabled the study to identify opportunities, drawbacks, and open issues in improving the quality of technology-enhanced sustainability education.

Specifically, the qualitative evaluation of the experiments considered three dimensions: technical, human, and contextual factors, along with their related variables, which are respectively explained in Tables 2–4.

Table 2. Observation grid section A: Technical factors.

Dimensions	Descriptions	References
Device Readiness	Available, configured, and charged devices.	Pérez-Martínez, et al., 2023 [59]
Software Service Setup	Interoperable, active, and service	Gupta, 2023 [60]
Usability and Acceptance	Perceived usefulness, utility and usability.	Marian, et al., 2025 [61] Krouska et al., 2024 [62]

Table 3. Observation grid section B: Human factors.

Dimensions	Descriptions	References
Digital Literacy	Awareness, attitude and ability of individuals to appropriately use digital tools	Martinez, 2022 [63]
Affection	Affective engagement with sustainability issues by means of interactive technologies	Fritsch, 2018 [43] Fritsch, 2021 [64]
Green Competence	Awareness, knowledge, and attitudes towards Sustainability	Garito, et al., 2023 [65] Frisk et al., 2011 [66]

Table 4. Observation grid section C: Contextual factors.

Dimensions	Descriptions	References
Space	Availability of rooms and outdoor settings	Sharpe, Breunig, 2009 [67]
Time	Time poverty	Sarku et al., 2024 [68] Martey, Etwire, Krah, 2024 [69]
Infrastructure	Electric power and internet connection availability	Aung, Khaing, 2016 [70] Widdicks et al., 2022 [21]

Table 5 displays the chronological sequence of the co-design activities and the related interactive prototypes for each specific educational context.

Table 5. Planning of the qualitative experimental studies.

Experimental study	Institution, Country, Date	Interactive Prototype
Study 1	Ellinogermaniki Agogi School in Athens, Greece, May 2022	GreenVerse 360° Interactive Documentary Platform
Study 2	Aurel Rainu High School in Fieni, Romania, November 2023	Environmental Monitoring Mobile Application
Study 3	Largo Cocconi High School in Rome, Italy, February 2024	CleanAir@School

The three studies involved testing prototypes at various stages of the research, each with different levels of maturity and readiness. They used not only different technologies but also varying levels of accuracy, completeness, and validation.

Every experimental study is explained, detailing the Instructional Co-design workshop protocol used to organise the workshop, the practical in situ activities carried out to test a given learning experience and its assigned interactive prototype, and the final information collected from field observation. Despite the variety of learning aims, functions, and expected outcomes proposed and elicited by the different interactive technologies, all three experimental activities followed the same protocol. Tasks 1 and 2 relate to activities carried out during the Instructional Co-design workshop, while Tasks 3 and 4 refer to those experienced during the in situ studies.

5.1. Study 1: Ellinogermaniki Agogi School in Athens, Greece, May 2022

5.1.1. Study 1: Instructional Co-Design Workshop

Task 1—Strategy and technology setup. The scenario was situated within the Biodiversity macro-area of the European Green Deal, specifically targeting competences related to understanding existing ecological challenges, preserving the authenticity of local flora and fauna, and recognising the value of native species.

In collaboration with the educators, the research team chose to integrate the GreenVerse 360° Interactive Documentary Platform into a technology-enhanced learning scenario.

Task 2—Instructional design. The first Instructional Co-design workshop activities were conducted at the Ellinogermaniki Agogi School in Athens, Greece, to collaboratively develop a learning scenario alongside local educators that fosters students' active engagement in both tangible and intangible world heritage conservation. The pedagogical objective was to enhance students' awareness of the importance of safeguarding natural and cultural sites to ensure their long-term sustainability. The class design was oriented toward producing an interactive journalistic report or documentary that addressed a real environmental phenomenon, either one that threatened or supported the conservation of the local green site surrounding the institution. Students worked in groups of three, and the practical activities were structured into three main stages:

1. Exploration and discovery, involving the use of mobile devices to examine the local green site and record environmental features by generating digital evidence.
2. Content elaboration and storytelling, in which students selected content and constructed the narrative for their journalistic report.
3. Scenario building, in which the groups created immersive 360° environments within the GreenVerse platform to present their findings.

Learning outcomes were evaluated through the communicative effectiveness of the digital artefacts, with particular attention to the environmental messages and stories conveyed through the immersive experiences.

5.1.2. Study 1: Educational Activity Execution

Task 3—Learning format execution. The in situ study was conducted over a four-hour session and involved four groups of students. The activity began with a 30 min introductory presentation, during which the research team outlined the topic, learning objectives, and expected outcomes, and provided an orientation to the GreenVerse platform (Figure 2).

Figure 2. Introduction to the GreenVerse platform presented to the Greek study participants. Source: Authors.

Following the introduction, students were presented with the educational challenge and divided into groups, each receiving a tablet equipped with Google Workspace 2022 and an institutional account. Over the course of 45 min, groups explored the school's surroundings, documenting environmental phenomena by capturing photographs and conducting interviews with educators through video or audio recordings. The multimedia evidence collected was stored in cloud-based institutional folders within Google Drive, forming the material base for subsequent documentary development.

In the second phase, students began designing their journalistic reports by structuring narratives through the storyboard technique. Working with analogue tools—such as A3 sheets, pens, and markers—they envisioned the progression of their interactive stories. This stage lasted approximately 45 min. The third and final phase, lasting two hours, involved translating the storyboards into immersive, interactive documentaries using the GreenVerse platform. As the prototype functioned as a post-production web tool, students accessed it exclusively through researchers' laptops via institutional credentials. Groups uploaded their collected multimedia files from Google Drive into the GreenVerse workspace, creating a user-generated multimedia library. These files were subsequently integrated into 360° environments, which utilised panoramic photos or videos as backgrounds and were enriched with annotations (e.g., images, videos, audio, text, or hyperlinks) to enhance narrative depth and engagement. The platform's preview mode allowed students to visualise their work in a simulated published format.

Task 4—Learning evaluation. At the conclusion of the activity, each group presented their interactive artefacts to the educators, who evaluated the effectiveness and communicative clarity of the messages conveyed through the immersive documentaries.

5.1.3. Study 1: Field Notes

The activities conducted by the researchers in the first experimental study in Greece generated several field notes alongside all four tasks examined in Section 3.3, which are reported in Table 6.

Table 6. Field notes from the initial experimental study conducted at the Ellinogermaniki Agogi School in Athens, Greece, are organised into the nine dimensions considered in Tables 2–4.

#Note	Dimension	Task	Comment
01-1-T1-DR	Device Readiness	1	By having to carry out interviews, the participants were provided with mobile devices.
02-1-T2-DR		2	The limited number of available devices forced the students to work in restricted groups.
03-1-T3-DR		3	A specific device, not accessible to anyone, was needed to create 360° images.
04-1-T1-SS	Software Service Setup	1	Participants needed a registered account to access the GreenVerse technology
05-1-T2-SS		2	Institutional devices were impossible to unlock because the institutional password had been forgotten.
06-1-T3-SS		3	Large field picture and interview recording files were unable to be uploaded to the GreenVerse due to their large size.
07-1-T3-SS		3	The Greenverse platform did not support the audio and video files created by mobile devices.
08-1-T3-SS		3	The Greenverse platform was unable to open specific web links due to a privacy issue.
09-1-T1-UA	Usability and Acceptance	1	No usage instructions were provided on the GreenVerse platform.
10-1-T3-UA		3	Students found the 3D spherical view challenging because it demanded advanced abstraction skills and a good grasp of perspective.
11-1-T4-UA		4	The GreenVerse offered a navigation model in 360° environments that was challenging for educators to use.

Table 6. *Cont.*

#Note	Dimension	Task	Comment
12-1-T3-DL	Digital Literacy	3	Educators were not prepared to assist students in using the GreenVerse technology.
13-1-T3-DL		3	Students lacked the competence to generate 360° images of videos.
14-1-T2-AF	Affection	2	The systemic complexity of the climate crisis hinders students’ understanding of its negative effects.
15-1-T4-AF		4	Using visual and interactive resources and narrations helped students empathise with a specific environmental issue.
16-1-T1-GC	Green Competence	1	Most of the involved educators felt ill-prepared to teach sustainability education.
17-1-T2-GC		2	Students needed an initial introduction to sustainability to grasp the complexity of the domain.
18-1-T4-GC		4	Educators lacked a proper assessment method to evaluate the students’ outcomes.
19-1-T1-SP	Space	1	The educational setting required a specific classroom equipped with a projector and plugs.
20-1-T2-SP		2	The institution was unable to provide sufficient outdoor space for sustainability education activities because of its building architecture.
21-1-T1-TI	Time	1	The educators’ lack of time forced them to shorten the educational experience
22-1-T3-TI		3	Understanding the technology proved challenging, resulting in a delay in implementing the activity.
23-1-T4-TI		4	The educators needed time to assess the complexity of the qualitative parameters of the outcomes.
24-1-T2-IN	Infrastructure	2	The technology implemented requires an internet connection.
25-1-T3-IN		3	Slow internet speeds hindered data transfer from mobile devices to the GreenVerse library.

5.2. Study 2: Aurel Rainu High School in Fieni, Romania, November 2023

5.2.1. Study 2: Instructional Co-Design Workshop

Task 1—Strategy and technology setup. As in the first study, the scenario was situated within the Biodiversity macro-area of the European Green Deal, targeting competences related to understanding ecological challenges, preserving the authenticity of native flora and fauna, and recognising the value of local species.

Together with the participating educators who reunited at Aurel Rainu High School in Fieni, Romania, the research team integrated the Environmental Monitoring Mobile Application into a technology-enhanced learning scenario.

Task 2—Instructional design. The second Instructional Co-design workshop activity was carried out in collaboration with the Volens Association. This non-profit organisation facilitated engagement with educators from five educational institutions in Dâmbovița

County, Romania: Diaconu Coresi Secondary School, Aurel Rainu High School (Fieni), Lucieni Secondary School, Ion Ciorănescu Secondary School (Moroeni), and Elena Donici Cantacuzino Secondary School (Pucioasa).

The participatory activities aimed to collaboratively design a learning scenario that raised awareness of the effects of environmental pollution on the extinction of animal and plant species in the local area (Figure 3).

(**a**) (**b**)

Figure 3. Teachers are learning to use the Environmental Monitoring mobile app to structure the classroom orchestration during the on-field testing activity. (**a**) Teachers trying the app outdoors to set up and configure their devices; (**b**) teachers involved in instructional co-design. Source: Authors.

The pedagogical objective was to promote students' active engagement in safeguarding and preserving natural sites as a means of mitigating biodiversity loss.

The learning activities focused on local biodiversity and mapping species in various areas of Dâmbovița County, thereby enabling comparisons across districts and fostering reflection on the causes and consequences of biodiversity loss. Students worked in groups of three, and the activities were structured into three stages:

1. An exploration walk, during which students used the interactive prototype to investigate local habitats and document natural species through digital images.
2. A Comparative analysis, in which students compared the recorded data across districts, identifying areas with lower species diversity and discussing potential drivers of biodiversity decline.
3. A Photo exhibition, where groups curated and presented their findings, highlighting distinctive species and proposing sustainable measures to prevent biodiversity loss and extinction. Learning outcomes were assessed through the communicative effectiveness of the exhibitions, with particular emphasis on the selection, representation, and interpretation of local species of flora and fauna.

5.2.2. Study 2: Educational Activity Execution

Task 3—Learning format execution. The second in situ study was conducted over three separate sessions, each dedicated to a specific activity: (1) an expedition, (2) data analysis, and (3) the organisation of a photo exhibition. The study involved 60 students from three classes of the Elena Donici Cantacuzino Secondary School in Pucioasa, Romania. Before the start of the activities, a 30 min introductory session was held the day before to present the educational challenge, outlining its purpose, function, and expected outcomes. During the session, students were divided into groups and trained in the use of the Environmental Monitoring Application.

This interactive prototype was designed to enable registered users to generate comprehensive environmental reports for a given territory. Each report consists of a title, a detailed description of the identified issue, and supporting multimedia evidence (e.g., photographs, videos, documents, or text) that users have produced or uploaded. All reports are georeferenced and classified according to predefined categories of criticality: risk, emergency, pollution, and solution. A map-based interface displays all available reports based on their geographic coordinates, allowing institutional administrators to review and validate submissions to prevent duplication, inconsistencies, or irrelevant entries. The application also requires GPS authorisation to track device location accurately. On the first day of the study, educators organised a four-hour walking tour during which students used the application to photograph and geolocate species of plants and animals in the surrounding area. This activity enabled the creation of a shared digital map of local flora and fauna, while also highlighting environmental issues that could threaten biodiversity (Figure 4).

Figure 4. Students of Romanian studies participate in a walking tour to map the local flora and fauna. Source: Authors.

On the second day, students collaborated with educators to analyse and compare their findings across different sites in Pucioasa. Educators, in their role as administrators, examined and approved each report to ensure content reliability. By considering the frequency and distribution of observed species, students constructed a biodiversity map of the area and identified zones where human impact was most evident. Following the analysis, students produced explanatory posters combining text and images to document the characteristics of the species encountered and reported during the expedition. The data analysis lasted two hours, while poster design and preparation required an additional one hour and 30 min.

Task 4—Learning evaluation. The third day of the study was dedicated to preparing and installing a photo exhibition within the school premises, which remained open for one month. The exhibition was formally inaugurated through group presentations in which students introduced their artefacts and explained the messages behind their visual narratives. Educators evaluated the final products, focusing on the communicative clarity and effectiveness of the posters and images in conveying biodiversity-related issues and potential pathways for preservation.

5.2.3. Study 2: Field Notes

The researchers' activities during the second experimental study in Romania produced several field notes, organised into the four tasks discussed in Section 3.3, which are summarised in Table 7.

Table 7. Field notes from the second experimental study at Elena Donici Cantacuzino Secondary School in Pucioasa, Romania, are organised according to the nine dimensions described in Tables 2–4.

#Note	Dimension	Task	Comment
01-2-T1-DR	Device Readiness	1	The activity implementation required the participants to own mobile devices.
02-2-T2-DR		2	The school was not able to provide enough mobile devices to the participating students.
03-2-T4-DR		4	To approve the students' content, the app required the administrator to use a desktop version, typically a laptop.
04-2-T1-SS	Software Service Setup	1	Participants needed a registered account to access the app.
05-2-T1-SS		1	The app required a teacher to register as an administrator to monitor and approve the students' generated content.
06-2-T2-SS		2	The app required the mobile phone user's permission to enable the GPS function.
07-2-T3-SS		3	The app software prototype did not ensure compatibility with old iOS and Android operating systems, especially regarding GPS feature activation.
08-2-T3-SS		3	Android phones made GPS activation more difficult due to incompatibility with the app's privacy settings.
09-2-T2-UA	Usability and Acceptance	2	The lack of accurate geolocation feedback from the app hindered educators' ability to evaluate its effectiveness.
10-2-T2-DL	Digital Literacy	2	Educators could not independently set up the GPS private permission.
11-2-T3-DL		3	Configuring privacy settings for the GPS proved to be a challenge for the students, requiring assistance from the research team.
12-2-T2-AF	Affection	2	Students struggled to grasp the concept of biodiversity loss because it lacks visible and tangible evidence.

Table 7. *Cont.*

#Note	Dimension	Task	Comment
13-2-T3-AF		3	Working in actual real-world settings enhanced students' understanding of sustainability concepts.
14-2-T4-AF		4	Working in groups helped students to improve their active collaboration with one another.
15-2-T4-AF		4	Addressing local issues enhanced attachment and a sense of belonging, connected to the protection of the local territory.
16-2-T1-GC	Green Competence	1	Educators requested additional complementary training to increase their awareness and competencies in sustainability education.
17-2-T3-GC		3	Students struggled to recognise endemic species in their local area, particularly those at risk of extinction.
18-2-T4-GC		4	Educators lacked an appropriate assessment method to accurately evaluate the qualitative aspects of students' outcomes.
19-2-T2-SP	Space	2	Learning activities on biodiversity required access to the natural environment to be effective, which was not available inside the school's property.
20-2-T1-TI	Time	1	The lack of time increased the need for educators for pre-defined learning modules that can be easily integrated into students' curricula.
21-2-T2-TI		2	Access to natural sites in the neighbourhood of the school required time for educators to plan and obtain permission for the walking tour.
22-2-T1-IN	Infrastructure	1	The mobile App required an internet connection to work.
23-2-T2-IN	Infrastructure	2	Using mobile devices in open public spaces requires access to a mobile data internet connection.

5.3. Study 3: Largo Cocconi High School in Rome, Italy, February 2024

5.3.1. Study 3: Instructional Co-Design Workshop

Task 1—Strategy and technology setup. The learning scenario was situated within the Zero Pollution macro-area of the European Green Deal, specifically targeting competences related to ensuring clean, safe air quality for human life and protecting human health by reducing the impact of pollutant emissions into the atmosphere.

For the experimental study, the research team and educators chose to adopt the CleanAir@School demonstrator (developed by the project partner 4Sfera, located in Girona Spain) as a technology-enhanced learning solution to create a learning scenario in sustainability education.

Task 2—Instructional design. The third and final Instructional Co-design workshop was held at the Largo Cocconi High School in Rome, Italy. It involved local educators in planning a learning scenario to help students raise awareness of air quality (Figure 5).

The pedagogical objective was to foster deep learning and critical engagement on air pollution, including education and understanding the fundamental aspects of this environmental phenomenon, such as its signs, typologies, sources, and impact on human health, and familiarisation with a scientifically based analysis approach, encompassing documentation, analysis, measurement, evaluation, and improvement.

Figure 5. Introduction to the Instructional Co-design workshop activities, featuring the CleanAir@School prototype and the educators involved in the Italian study. Source: Authors.

The class design focused on collecting and measuring data with analogue passive sensors, and subsequently developing artefacts, such as presentations and posters, to report and highlight the real air quality situation around the Italian institution, the Centocelle suburban area in Rome, to its residents. The practical activities were carried out by student classes and organised into a structured two-month timeline, as outlined below:

1. Sensor placement and measurement strategies involve educators selecting key urban locations and busy areas with high traffic mobility to assess air quality. This assessment utilises a nearby reference air quality station, situated near the institution, to ensure measurement accuracy.
2. Exposure time, during which the groups could wait for the samplers' passive measurement while regularly checking if they were not damaged or stolen by external factors and learning about air pollution.
3. Sensors and data collection involve educators and students re-collecting the samplers and sending them to the laboratory for data analysis.
4. Data analysis and presentation, where the laboratory supplies educators and students with an air quality report. They can then extrapolate quantitative data and create informative posters to raise awareness of the air quality around the institution.

Learning outcomes were evaluated through the communicative effectiveness of the final artefacts, with an explicit focus on the comprehensibility of the air quality phenomenon conveyed through its scientific and analytical narrative.

5.3.2. Study 3: Educational Activity Execution

Task 3—Learning format execution. The in situ study was conducted over a period of two months. It involved four classes of primary school students, comprising a total of 73 students: 14 third-grade students in the first class, 17 third-grade students in the second class, 22 fifth-grade students in the third class, and 20 fifth-grade students in the fourth class. The study commenced with an introductory session, during which the purpose, function, and expected outcomes of the CleanAir@School demonstrator were presented to the participating classes.

The first phase of the activity focused on the collective installation of 100 passive nitrogen dioxide (NO_2) samplers, provided by the research team, to monitor local air quality. Students and their families carried out the installation under the guidance of educators to foster collective awareness of air pollution. To support geolocation and exposure tracking, teachers registered on a dedicated digital application (https://greenscent.4sfera.eu/ (accessed on 30 July 2025)) and completed a preliminary virtual mapping of the sensors before their physical deployment (Figure 6).

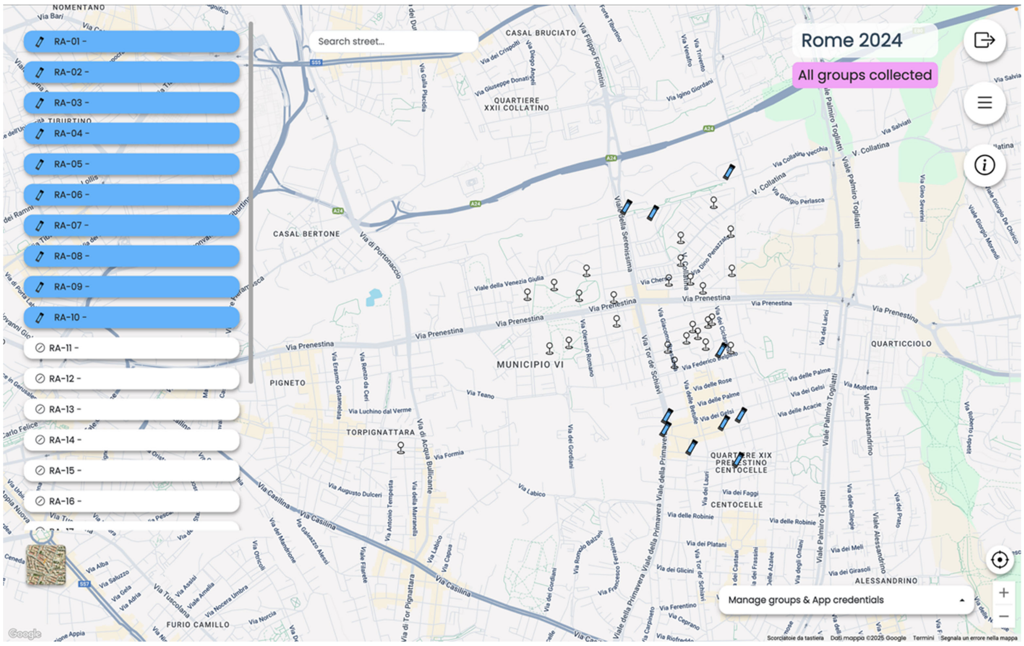

Figure 6. Desktop version of the digital application for the CleanAir@School prototype, which assisted educators in virtually mapping the positions of passive sensors in the city of Rome. The left panel shows the sensor identification codes on the platform. The blue colour fill indicates the physical deployment of some samplers, while the white colour fill shows those that have not been deployed yet. Source: Authors.

The installation phase consisted of two complementary actions: a collective installation of 40 sensors in the vicinity of the school, conducted through a walking tour in collaboration with the four classes, and an individual installation of 60 sensors carried out by students and their families in their residential areas. Each sampler was registered in the digital application's virtual map by scanning its QR code, photographing the device, and assigning an identification code along with the initial date and time of exposure. Students carried out these registration activities, assisted by their educators and using their smartphones for the first 40 sensors, while the remaining 60 were registered with the help of their parents.

The second phase consisted of a four-week monitoring period. During this time, educators integrated principles of air pollution into regular lessons to prepare students for data interpretation and analysis. Teachers and students were also responsible for periodically checking the sensors' operational status to ensure data reliability.

At the conclusion of the exposure period, educators, students, and their parents collected the samplers, again scanning the QR codes through the mobile app to verify their correspondence with the virtual map and to record the end date and time of exposure. The devices were then stored and sent to the research team's laboratory for analysis (Figure 7).

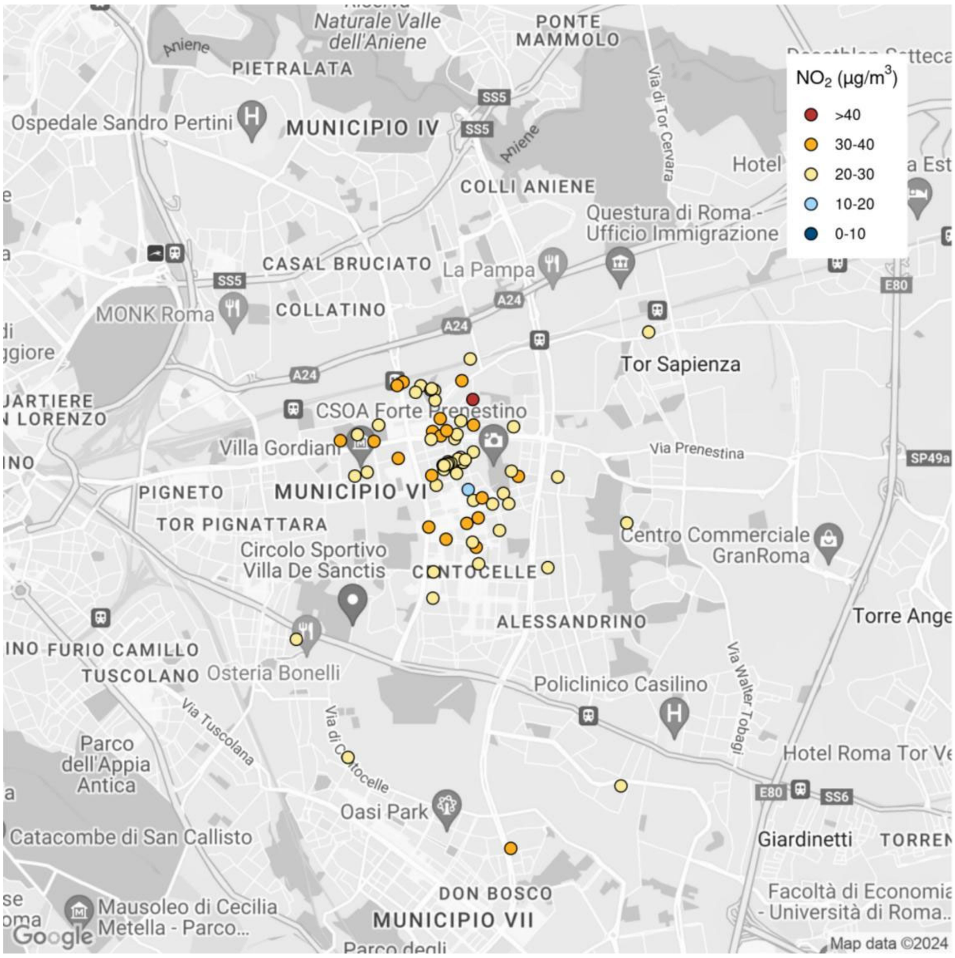

Figure 7. Virtual heat map of average NO_2 levels in Rome, created using the digital application for the CleanAir@School prototype. Source: Authors.

Two weeks later, each of the four classes received a detailed report on nitrogen dioxide concentrations in the area surrounding their school. These results were subsequently examined in class, where students and educators collaboratively produced visual narratives and scientific artefacts to represent the findings.

Task 4—Learning evaluation. The learning activity concluded with the presentation of scientific posters by the four classes, which educators evaluated in terms of the communicative clarity, accuracy, and effectiveness of the messages conveyed through the information, graphics, and interpretations provided.

5.3.3. Study 3: Field Notes

The researchers' activities in the third experimental study in Italy produced several field notes, along with all four tasks discussed in Section 3.3, which are summarised in Table 8.

Table 8. Field notes from the third experimental study at Largo Cocconi High School in Rome, Italy, are organised into the nine dimensions outlined in Tables 2–4.

#Note	Dimension	Task	Comment
01-3-T1-DR	Device Readiness	1	The activity implementation required that the participants have their own mobile devices.
02-3-T2-DR		2	The school was unable to provide all the necessary mobile devices to the participating students.

Table 8. *Cont.*

#Note	Dimension	Task	Comment
03-3-T2-DR		2	The school needed to give educators laptops to register the sensors.
04-3-T3-DR		3	Students who installed the sensors with their families had to depend on their parents' digital devices and internet connection.
05-3-T1-SS	Software Service Setup	1	Participants needed a registered account to access the app.
06-3-T12-SS		2	The app required user permission to enable the camera and GPS functions.
07-3-T3-SS		3	Manually scanning and numbering the sensors using the QR code delayed the installation and collection activities.
08-3-T2-UA	Usability and Acceptance	2	The sensor registration was not designed for mobile-first interfaces and required a desktop computer.
09-3-T2-UA		3	The lack of clear visual cues to organise the sensors into groups caused the educators to record only half of the total dosimeters.
10-3-T1-DL	Digital Literacy	1	Educators require training to understand how to apply the CleanAir@School prototype in real-life settings.
11-3-T2-DL		2	Educators needed training to learn how to effectively interact with the mobile application and accurately record sensor data.
12-3-T3-DL		3	Students who installed the sensors with their families had to depend on their parents' technology literacy.
13-3-T1-AF	Affection	1	The concept of air quality was a sensible topic for educators due to air pollution caused by constant heavy traffic around the school.
14-3-T2-AF		2	Students felt detached from air pollution issues because it is an invisible phenomenon, making it difficult to comprehend.
15-3-T3-AF		3	Parents gained increased awareness of air pollution by actively supporting their children in practical activities.
16-3-T4-AF		4	Addressing local issues enhanced attachment and a sense of belonging, with a connection to the protection of the local territory.
17-3-T4-AF		4	The app increased students' awareness by visually representing invisible phenomena, such as air quality.
18-3-T2-GC	Green Competence	2	Students required a dedicated learning session to get introduced to air pollution.
19-3-T3-GC		3	Parents learned about air pollution by actively supporting their children in practical activities.
20-3-T4-GC		4	Educators lacked an appropriate assessment method to accurately evaluate the qualitative aspects of students' outcomes.

Table 8. *Cont.*

#Note	Dimension	Task	Comment
21-3-T4-GC		4	Students required educators' support to interpret the scientific information described in the final report.
22-3-T2-SP	Space	2	Learning activities on air pollution required access to the urban environment beyond the school's premises.
23-3-T3-SP		3	The activity required specialised lab expertise for data analysis.
24-3-T1-TI	Time	1	The lack of educators' time heightened the need to give them predefined instructions on how to carry out learning activities.
25-3-T2-TI		2	Access to urban sites outside the school required time for educators to plan and obtain permission for the walking tour.
26-3-T2-TI		2	Educators lacked the time to dedicate to the preliminary virtual mapping of the sensors before their physical deployment
27-3-T3-TI		3	Installing and collecting the dosimeters demanded a high amount of time for the classes.
28-3-T3-TI		3	Monitoring the sensors' functionality required extra time for educators to supervise them throughout the exposure period.
29-3-T4-TI		4	Data analysis took a considerable amount of time to obtain results from the sensors, thereby delaying the institution's learning activities.
30-3-T1-IN	Infrastructure	1	The CleanAir web technologies required an internet connection.
31-3-T1-IN		1	The CleanAir technology required a reference air quality station near the school.
32-3-T2-IN		2	Using mobile devices in open public spaces requires access to a mobile data internet connection.

6. Discussion

In field research, investigators must be prepared to deviate from the initial study plan to accommodate emergent phenomena. The study, for instance, yielded more insights into organisational, human, and technical constraints, as well as how various stakeholders negotiated and navigated them, than it did into the efficacy of the tool itself. Furthermore, it provided valuable insights into the mechanisms of learning and teaching.

Research on technology-in-use demonstrates that the full impact and adoption of the resulting system cannot be predicted in a controlled laboratory setting. Therefore, iterative cycles of testing, observation, and adaptation are essential.

This premise was immediately confirmed during the real-world deployment of our initial technology prototype, leading the researchers to acknowledge a (not often) clear distinction between prototype and product, as well as between experiment and integration.

The three case studies, focusing on the Greenverse Interactive Documentary, the Environmental Monitoring app, and the CleanAir@School initiative, demonstrate the critical interplay between technological affordances, pedagogical considerations, and the realities of resource finiteness. To support readability, the findings are described according to the three domains—technical, human, and contextual factors—targeted in the research (see the Observation grids in Tables 2–4). At the same time, in each aspect, there are cross-domain bridges that demonstrate the complex interplay of socio-technical systems.

6.1. Findings on Technical Factors

As for the technical factors, we highlight the following:

- Interoperability and Compatibility: Issues arose with file format compatibility, data transfer limitations, and integration with existing platforms (e.g., Environmental Monitoring with Android OS, see 07-2-T3-SS, 08-2-T3-SS; privacy settings, see 08-2-T3-SS). These challenges underscore the need for robust interoperability and compatibility among different technologies and platforms to ensure seamless data flow and a consistent user experience. When technologies are not fully integrated to exchange data, a developed digital literacy is indeed implied, e.g., for configuring privacy settings, see 11-2-T3-DL.
- Technology readiness and efficacy: Limitations in internet connectivity, device availability (see 02-3-T2-DR, 03-3-T2-DR, 01-2-T1-DR, 02-2-T2-DR), and access to reliable power sources significantly impacted the effectiveness of technology-enhanced learning activities (e.g., slowness in execution, see 25-1-T3-IN; support for indoor and outdoor activities, see 23-2-T2-IN and 22-3-T2-SP). The implementation and adoption of prototypes (see 07-2-T3-SS) also affect readiness and understandability among educators (see 09-2-T2-UA), who may not always have expertise in computer science and consumer electronics to solve technical issues, such as GPS management (see 10-2-T2-DL) and privacy settings (see 11-2-T3-DL).

6.2. Findings on Human Factors

Regarding human factors, we consider the following relevant:

- Teacher preparedness and Green Competence: The effective integration of technology into educational settings requires adequate teacher training (see 16-1-T1-GC, 18-1-T4-GC, 16-2-T1-GC, 18-2-T4-GC, 20-3-T4-GC). The case studies demonstrated that insufficient teacher training and preparedness can lead to challenges in technology implementation, such as managing access and users' permissions (see 03-2-T4-DR, 05-2-T1-SS), and affect the effectiveness of their educational interventions, particularly due to their lack of competence (see 16-2-T1-GC, 21-3-T4-GC).
- Assessment and Evaluation: The evaluation of technology-enhanced learning experiences and outcomes requires robust assessment methodologies that go beyond traditional measures of student performance and consider factors such as student engagement, critical thinking skills, and the development of digital literacy (see 18-1-T4-GC, 18-2-T4-GC, 20-3-T4-GC). Artefacts such as interactive documentaries, evidence-based interactive maps, and multimedia communication campaigns need to be assessed in conjunction with individual learning performance and formal knowledge acquisition. They not only convey students' knowledge about Green Deal issues (see 21-3-T4-GC, 18-3-T2-GC) but also increase their engagement with and affection towards sustainability (see 14-3-T2-AF) beyond the support of teachers and parents (see 13-3-T1-AF, 15-3-T3-AF, 19-3-T3-GC).

6.3. Findings on Contextual Factors

The contextual factors coming out of the analysis are as follows:

- Curriculum Integration: Seamless integration of technology into the existing curriculum is crucial for successful implementation. The case studies highlighted the need for careful planning and consideration of pedagogical approaches that effectively leverage technology to enhance learning outcomes (see 20-2-T1-TI, 21-2-T2-TI, 21-1-

T1-TI). Having sustainability education integrated into the curriculum implies having the necessary time for familiarisation and management of technology (see 22-1-T3-TI, 26-3-T2-TI, 27-3-T3-TI, 28-3-T3-TI) and to develop assessment methodologies for the experiential, technology-enhanced, and transformational learning scenario being tested (see 23-1-T4-TI and 18-2-T4-GC).

- Affection for local community: There is a need to ensure equitable access to technology and digital resources for all users, regardless of their socioeconomic background, and that this access would favour the belonging to the local community (see 16-3-T4-AF), knowledge of local environmental phenomena (see 19-2-T2-SP and 15-1-T4-AF), and a sense of self-efficacy in managing systemic solutions for wicked problems (see 14-1-T2-AF). By highlighting invisible aspects of sustainability issues (see 17-3-T4-AF, 14-3-T2-AF, 17-2-T3-GC), digital technology increases affection, participation, and commitment towards pro-environmental behaviour, as well as individual and collective change (see 14-2-T4-AF).

7. Limitations of the Research

Educational initiatives and technologies are often designed for universal application across diverse urban and rural environments, transcending national and local boundaries. However, the complexity arising from a multitude of contextual factors frequently limits their full deployment, especially for sustainability education technologies in resource-constrained settings. The research highlights the importance of in-depth, in situ experimentation, data collection, and analysis to prevent the misuse of technology and misinterpretation of educational models.

Our three field experiences revealed critical aspects that, while initially slowing down co-design activities, generated valuable insights for improving sustainable design practices in resource-limited scenarios. Specifically, the following elements warrant consideration:

- Inclusion: Our initial design research in Greece took place in a socio-economically privileged environment with a potential predisposition toward environmental issues. It necessitated extending the research to less privileged environments to ensure a broader, more representative sample. We included low-tech schools in rural Romania and suburban areas of Rome, Italy, serving students at risk of exclusion from university. These cases highlight significant challenges in providing digital educational resources to vulnerable groups, including time poverty, limited financial and technological resources, inadequate digital connectivity, and insufficient background knowledge about sustainability. A key finding was the difficulty secondary school teachers had in adopting a competency-based approach to teaching sustainability. It highlights the critical need for tailored training materials and ongoing support. Furthermore, the Greek case study demonstrated that even in high-resource settings, successful technology adaptation and inclusion are not guaranteed, as limitations can arise independently of economic or technological factors.
- Down-scalability: Although our project utilised innovative, technology-enabled pedagogies, their implementation revealed that some contexts lacked essential resources, such as background knowledge, connectivity, devices, and, crucially, time. To ensure the replicability of educational activities across diverse socio-economic and cultural settings, we must develop technologies adaptable to resource-constrained environments. It includes minimising the environmental impact of technology throughout its lifecycle. A viable strategy is to downscale technological requirements. For instance, transforming an interactive journalistic narrative from a platform like the GreenVerse 360° Interactive Documentary into an analogue, paper-based experience can overcome infrastructural limitations. This approach ensures the same core sustainability

education message is delivered through a creative and engaging format, even in low-resource scenarios.

- Trade-off Between Readiness and Contextualisation: A central challenge is the tension between a tool's readiness for immediate use and the need to customise it for specific contexts. Adopting a competence-based, technology-enhanced teaching method requires significant temporal, digital, and cultural resources, which are often unavailable to educators. To mitigate this, our research provides a heterogeneous range of teaching activities, making it easier for educators to select tools and scenarios that align with their available resources and specific contexts.

As the research continues to address a competency-based approach, new challenges are anticipated, particularly concerning varying levels of digital and cultural literacy, technological availability, and socioeconomic environments. Any educational tool or initiative requires adaptation to the specificities of each setting, a process that is both time-consuming and resource-intensive. Despite these challenges, the importance of competency-based environmental education cannot be overstated.

8. Conclusions

When considering resource finiteness scenarios, the primary goal of design action should not be economic growth, but rather the well-being of humans and other species. It requires a more equitable and inclusive approach that considers the needs of disadvantaged communities and promotes social justice [71–73].

A diminished availability of resources occurs in impoverished communities [74,75]. Therefore, designing adaptable technologies for contexts with limited resources, both now and in the future, is crucial [76,77]. Understanding sustainability takes on different meanings depending on the context. Interaction systems must be tailored to specific local contexts, taking into account local resources, environmental conditions, cultural norms, and user skills and values [78]. It implies creating simple, modular software capable of running on existing hardware and prioritising community needs [79].

Together with system infrastructures and mitigation of material resource consumption, designers' and developers' commitment should be to adopt regenerative practices. Permacomputing [80], inspired by permaculture, presents a promising approach to design that emphasises diversity, longevity, reuse, and repair, rather than planned obsolescence [81,82]. Regenerative practices in interaction design also challenge the design for social interaction, individuation, and empowerment, prioritising people's competencies, needs, expectations, and talents [83].

In conclusion, thinking about sustainability *-through* and *-in* design presents significant conceptual, societal, ethical and technological challenges, necessitating a holistic approach considering the human, technical and contextual opportunities and constraints. It aligns with principles like emphasising understanding, affection, belonging, competence, and addressing technology's social, environmental, and economic impacts. It thus must embrace transdisciplinarity, combining sustainability education, instructional design, and technology-enhanced learning [84,85].

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