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From Users to Designers: An In-Service Teacher Workshop for Mobile Game-Based Learning Experiences

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Abstract

STEAM approaches create new opportunities for students to develop thinking skills connected to technical and scientific education. By combining different areas of knowledge, STEAM encourages students to explore ideas from multiple perspectives and find creative solutions to challenges. This approach is highly relevant in teacher training, as it prepares educators to create innovative and engaging learning experiences. This study examines how an accredited teacher professional development workshop supported in-service secondary teachers in designing mobile game-based learning experiences for sustainability through the integration of STEAM, Universal Design for Learning, and Open Schooling. The study adopted a qualitative case study design based on thematic analysis of documents related to games created by teachers, implementation presentations, and teachers' reflections. The analysis shows that teachers engaged with educational technology in an authorial and design-oriented role, creating and refining situated digital resources. Teacher authorship and mobile learning design capacity were most prominent; UDL appeared mainly through multimodal and motivational features, alongside perceived student engagement. Technological reliability, accessibility, and data-validity issues remained important constraints. This context supported professional development by enhancing teachers' capacity to design STEAM, multimodal, and place-based digital learning experiences for sustainability, while articulating the OpenUS4ALL and EduCITY projects.

Keywords: digital game-based learning; Education for Sustainable Development; Open Schooling; STEAM education; Universal Design for Learning

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1. Introduction

Mobile technologies have become increasingly embedded in the everyday lives of children and young people, influencing educational thinking and practice by evolving from a peripheral topic into a consolidated field of research. Recent scholarship highlights a sustained interest in learner engagement, contextualized learning, and the pedagogical use of emerging technologies, such as augmented reality (AR) and app-based environments [1]. In parallel, mobile game-based learning has gained relevance as it extends education beyond the classroom, enabling situated, interdisciplinary experiences that foster active participation and motivation [2].

This technological evolution is particularly significant for Education for Sustainable Development (ESD), which requires pedagogical models that promote critical thinking and

action in authentic contexts. Recent research suggests that digital game-based and mobile AR approaches can make sustainability issues more tangible and engaging, particularly when they are connected to authentic, real-world contexts and carefully designed learning scenarios [3–5]. These possibilities are enhanced when games are embedded in outdoor learning ecologies, allowing learners to connect curricular knowledge with real-world, place-based challenges.

In this regard, the Open Universal STEAM for All (OpenUS4ALL) initiative (ref. 2023-1-ES01-KA220-SCH-000166940) seeks to support secondary school teachers in designing flexible Science, Technology, Engineering, Arts and Mathematics (STEAM)-oriented pedagogical projects. Rather than being used here as a theoretical source, OpenUS4ALL provides the project and training context for the present study. The analytical framework draws instead on established literature on STEAM education, Universal Design for Learning (UDL), and Open Schooling to examine how these principles were operationalized in teacher-created mobile learning resources. To operationalize these principles, the training was articulated with EduCITY, which provided the technological and pedagogical environment for authoring and implementing the mobile games. In this collaborative framework, teachers involved in the OpenUS4ALL training used the EduCITY mobile application as a platform to design specific games for their own cities, serving as a practical example of a smart learning city environment. By placing students at the center of real-world challenges, this synergy fosters key competencies aligned with the Sustainable Development Goals (SDGs).

Despite the potential of these combined frameworks, a significant gap remains between the theoretical possibilities of mobile game-based learning and the professional knowledge required by teachers to implement them effectively. Recent research on teacher education indicates that integrating STEAM, sustainability and digital technologies requires more than technical competence, particularly when teachers must connect theoretical principles with real-world contexts and translate them into pedagogical designs [6–8]. Although research emphasizes that pedagogical quality depends on careful design, curricular alignment and the articulation between game mechanics and learning objectives [2,9,10], empirical understanding remains limited regarding how in-service secondary teachers design, implement, evaluate and reflect on teacher-authored mobile game-based learning resources that simultaneously address sustainability, STEAM integration, inclusivity through UDL, and community engagement through Open Schooling. In particular, less is known about how these principles are translated into concrete design decisions, what professional learning emerges through this process, and what challenges affect their implementation and potential transfer to practice.

The teacher training workshop examined in this article was designed as a direct response to this need. Accredited as a 26-h professional development workshop for teachers at the University of Aveiro, the initiative focused on empowering educators to become designers of interdisciplinary digital resources. The workshop proposed the development and implementation of educational games within the EduCITY app, ensuring articulation with the national curriculum and the specificities of the participants' teaching contexts.

Structured according to a socio-constructivist perspective, the workshop positioned trainers as facilitators and teachers as active designers and evaluators of innovation. This design aligns with contemporary understandings of effective teacher education, which emphasize collaboration, situated practice, and the co-construction of pedagogical knowledge. By linking professional development with pedagogical agency, the workshop aimed to transform teachers from passive recipients of technology into creators of inclusive, open, and meaningful learning experiences.

Against this background, the present study aims to examine the professional relevance of training actions with these characteristics. It explores how participation supports teachers' engagement with mobile game-based learning for sustainability, specifically through the analytical lenses of STEAM, UDL, and Open Schooling within the OpenUS4ALL training context and the EduCITY environment.

1. How does teacher participation in the workshop influence their ability to design mobile game-based learning experiences for sustainability?
2. How are STEAM, UDL, and Open Schooling principles integrated into the resources developed by teachers?
3. What challenges and opportunities emerge in the process of designing and implementing these interdisciplinary learning experiences?

This study is significant at several levels. From a research perspective, it contributes to the still limited body of work on teacher professional development specifically focused on mobile game-based learning in sustainability education, an intersection that recent literature identifies as promising but still insufficiently explored [1–3,6]. More specifically, it examines teacher professional learning through a design-oriented perspective, focusing on how teachers move beyond the use of educational technology to author, contextualize, test and refine digital learning resources. From a practical perspective, it provides insight into how teacher education initiatives can support the creation of open, interdisciplinary, and context-sensitive digital educational resources, while also addressing curricular needs and student learning difficulties identified by teachers themselves. From a pedagogical and methodological perspective, it illustrates the value of combining collaborative design, situated experimentation, and reflective inquiry within a professional development framework oriented towards innovation in teaching and learning. In this sense, the workshop provides a bounded case for examining how STEAM, UDL, and Open Schooling can be translated into teacher-designed mobile game-based learning experiences for sustainability.

The remainder of this paper is organized as follows. First, it presents the conceptual and training context underpinning the workshop. It then describes the design and implementation of the training action and discusses the main results and implications for teacher professional development and future educational practice.

2. Literature Review

The conceptual analysis in this study is grounded in established literature on STEAM education, UDL, Open Schooling, mobile learning, and teacher professional development.

The teacher training workshop examined in this study was structured around a set of integrated pedagogical approaches that provided the theoretical and practical scaffolding for the participants' professional development. Rather than being treated as isolated perspectives, these frameworks are understood as distinct but complementary analytical lenses for the design of inclusive, interdisciplinary, and context-responsive learning environments. STEAM primarily addresses interdisciplinary knowledge integration and problem-oriented learning; UDL focuses on anticipating learner variability and reducing barriers to participation; and Open Schooling emphasizes connections between schools, communities, stakeholders, and authentic societal contexts. Their combination therefore broadens the pedagogical possibilities of mobile learning design, while also increasing the complexity of translating these principles into coherent educational resources.

STEAM education extends STEM by incorporating the arts and humanities into interdisciplinary, problem-oriented learning experiences. This approach supports creativity, collaboration, contextualization and the mobilization of knowledge across disciplinary boundaries, while also emphasizing the relevance of real-world problems and socially meaningful learning [6–13]. However, the presence of content from multiple disciplines

does not in itself constitute meaningful STEAM integration; such integration depends on how disciplinary knowledge is articulated around shared problems, tasks, or contexts.

The UDL framework is designed to enhance teaching by proactively accommodating learner variability and reducing barriers to participation. It is structured around three core principles: multiple means of engagement, representation, and action and expression [14]. Recent literature further shows that UDL is particularly relevant in technology-enhanced learning environments, where multimodal resources, flexible forms of participation and accessibility-oriented design can support more inclusive educational experiences [7,15,16]. Within this study, UDL plays a critical role in examining whether STEAM-based mobile learning activities were designed in ways that were inclusive and responsive to learner diversity.

Importantly, multimodality alone should not be equated with full UDL implementation, which requires deliberate attention to learner variability across engagement, representation, and action and expression.

Grounded in open and community-connected education, Open Schooling positions schools as outward-facing learning environments that connect students, teachers, families, local communities and external stakeholders around authentic societal challenges. In the OpenUS4ALL framework, this orientation is articulated with flexible learning strategies, inclusive access to resources, personalized learning and the reduction of traditional barriers to participation [11,17–19]. In this study, OpenUS4ALL provides the project and professional development context, while Open Schooling constitutes the pedagogical perspective used to examine connections between learning, place, and community. EduCITY, in turn, provides the technological and pedagogical environment through which these connections can be operationalized in mobile, place-based and AR learning experiences linked to real urban and community contexts [4,20]. Accordingly, learning outside the classroom or in urban spaces is not treated automatically as Open Schooling; the analytical emphasis is on whether activities establish meaningful links with authentic contexts, communities, or societal challenges.

In technology-enhanced professional development, teachers are increasingly expected to move from transmissive uses of digital tools towards more design-oriented and facilitator roles. This shift requires opportunities to create, test and refine learning resources in collaborative, interdisciplinary and context-sensitive environments [7,8].

From this perspective, digital competence involves not only using technological tools, but also making pedagogical design decisions about content, tasks, resources, accessibility, context, implementation, and refinement. This design-oriented view provides the professional learning lens through which the present study examines teachers' engagement with mobile game-based learning.

2.1. Review of Related Empirical Studies

Empirical studies on mobile and digital game-based learning consistently highlight its potential to foster student engagement, collaboration and meaningful knowledge construction. Game-based environments can enhance cognitive, emotional and behavioral engagement when learning activities are intentionally aligned with pedagogical goals and learner interaction [9,21,22]. More specifically, these outcomes depend on pedagogical mechanisms embedded in the game experience rather than on the use of games or mobile devices alone. Appropriately calibrated challenge can contribute to learning both directly and through increased engagement [21], while authentic mobile activities can create opportunities for interaction, communication and collaboration [23]. In mobile contexts, exploration and interaction with real places can further connect curricular knowledge with situated observation and problem-solving. For example, mobile outdoor learning can promote conceptual change, knowledge transfer and stronger connections between curricular

content and everyday experiences [24]. Feedback can also support learners in evaluating responses, reconsidering decisions and progressively adjusting their understanding when it is meaningfully integrated with the learning task [3,9]. This situated and experiential dimension is especially relevant for sustainability education, where learners are required to engage with complex socio-environmental problems in contextually meaningful ways.

However, despite these promising findings, the literature also reveals significant challenges associated with the implementation of mobile game-based learning. Learning effectiveness depends strongly on instructional design quality, particularly the alignment between game mechanics, learning objectives, curricular requirements and implementation conditions [9,10]. Accordingly, challenge, feedback, collaboration, exploration and multimodal interaction should not be understood as inherently educational game features; their pedagogical value depends on how they are connected to explicit learning objectives and appropriate instructional support. High levels of engagement do not automatically translate into meaningful learning outcomes, especially when pedagogical structures are weak or poorly integrated. Furthermore, the integration of mobile and AR technologies introduces constraints related to technical infrastructure, accessibility, usability, and teacher preparedness. These limitations point to a persistent tension between the innovative potential of mobile game-based learning and the practical conditions required for its effective use in formal education settings.

Recent initiatives, such as the EduCITY project, demonstrate how mobile AR can support place-based and sustainability-oriented learning in smart learning city environments. By integrating routes, points of interest (POIs), augmented resources and game-based tasks, EduCITY transforms urban environments into interactive learning spaces connected to curricular and community-based challenges [4,20,25]. Within this type of environment, route navigation and POI-based tasks support situated exploration, while AR and multimedia resources can connect observation of place with curricular information and game-based problem solving. Empirical evidence suggests that these approaches can strengthen student motivation by making learning more situated, interactive and personally meaningful.

However, a tension remains between the theoretical potential of these frameworks and their implementation in formal educational contexts. While STEAM, UDL and Open Schooling are associated with interdisciplinarity, inclusivity and community-connected learning, their operationalization requires time, institutional support, teacher preparation and careful pedagogical design. Recent empirical research on sustainability education through Open Schooling illustrates this difficulty: teachers have encountered challenges in designing learning from authentic sustainability problems, collaborating across professional boundaries, coordinating with external partners, and creating teaching materials for unfamiliar forms of practice [26]. This tension is particularly relevant in technology-enhanced learning, where innovation may remain superficial if teachers are not supported in translating broad pedagogical principles into concrete tasks, resources, assessment strategies and implementation routines [6,15,17].

2.2. Research Gap

The primary research gap lies in the limited understanding of how STEAM, UDL, Open Schooling and teacher professional development can be effectively integrated and operationalized in secondary education through mobile game-based learning for sustainability. Although the individual benefits of these approaches are well documented [6,17,20], recent empirical research has addressed important but still largely separate aspects of this problem. Large-scale evidence from STEM teachers shows that digital professional development is positively associated with the integration of digital technologies into instruction

and that professional learning communities can strengthen this relationship [27]. Research in secondary education further shows how digitally supported professional development can engage teachers as active and reflective participants in professional growth [28]. In sustainability education, empirical studies of Open Schooling have identified substantial challenges when teachers translate authentic societal problems, cross-professional collaboration and community partnerships into everyday teaching practices [26]. However, these strands provide limited evidence about how in-service secondary teachers author, implement, evaluate and reflect on mobile game-based learning resources that simultaneously combine sustainability, interdisciplinary STEAM learning, inclusivity through UDL, and connections with authentic places and communities through Open Schooling. In particular, less is known about how these principles are translated into concrete design decisions, how professional learning develops through iterative resource creation and implementation, and what pedagogical, technological and assessment-related challenges affect their enactment and potential transfer to future practice. This study addresses this gap by examining how teachers engaged with EduCITY and OpenUS4ALL to design mobile game-based learning resources for sustainability.

This gap is particularly relevant from a professional development perspective, as teachers are increasingly expected to act as designers of complex learning environments but often lack the pedagogical and technological preparation to do so effectively. As a result, a disconnection persists between the theoretical potential of mobile and game-based learning approaches and their actual implementation in classroom practice. Addressing this gap requires investigating how teacher training initiatives can support the translation of these integrated frameworks into teacher-authored, actionable pedagogical practices, while documenting processes of design, implementation, reflection and potential transfer to practice.

3. Methodology

3.1. Research Design

This study adopted a qualitative case study design, supported by thematic analysis, to examine how an accredited teacher professional development workshop supported teachers in designing mobile game-based learning experiences for sustainability. A qualitative approach was appropriate because the study sought to understand pedagogical design processes, professional learning, and the situated integration of STEAM, UDL, and Open Schooling principles in teacher-created digital resources, rather than to measure causal effects or statistically generalizable outcomes [29,30].

The study was guided by three research questions:

1. How does teacher participation in the workshop influence their ability to design mobile game-based learning experiences for sustainability?
2. How are STEAM, UDL, and Open Schooling principles integrated into the resources developed by teachers?
3. What challenges and opportunities emerge in the process of designing and implementing these interdisciplinary learning experiences?

The research design was interpretive. It focused on documentary evidence produced throughout the workshop, including teacher-designed EduCITY games, implementation presentations, and individual and group reflections. These materials were treated as artefacts of professional learning and pedagogical decision-making, allowing the analysis to reconstruct how teachers translated the conceptual frameworks of the workshop into concrete mobile learning resources.

3.2. Context and Participants

The study was conducted within a 26-h accredited teacher professional development workshop entitled "Práticas interdisciplinares de Educação para a Sustentabilidade através de jogos móveis digitais" [Interdisciplinary Practices in Education for Sustainability Through Digital Mobile Games], implemented between September and November 2025 at the University of Aveiro, Portugal.

The workshop was developed within the scope of the OpenUS4ALL project and articulated with the EduCITY smart learning city environment. OpenUS4ALL provided the professional development context for integrating STEAM education, UDL and Open Schooling, while EduCITY provided the technological and pedagogical infrastructure through which teachers could create mobile, place-based educational games connected to real-world contexts.

The workshop involved 10 in-service secondary teachers, all of whom provided informed consent for research use. Teachers participated in the workshop through voluntary self-enrolment; therefore, the workshop cohort was self-selected rather than probabilistically sampled. As all 10 workshop participants consented to research participation, the analytical sample comprised the full workshop cohort. Given the voluntary self-enrolment and the bounded context of a single professional development workshop, the cohort should be understood as context-dependent rather than statistically representative of the wider population of in-service teachers. The participants represented three disciplinary groups within the Portuguese teacher classification system: Geography; Physics and Chemistry; and Biology and Geology. At the beginning of the workshop, teachers were organized into interdisciplinary groups, which were maintained throughout the design, implementation and reflection stages. Each group developed one EduCITY game, resulting in three teacher-created mobile educational games.

EduCITY games are educational multiple-choice interdisciplinary quizzes organized as outdoor paths that participants physically travel along. The questions require players to apply subject-specific knowledge to authentic contexts observed in the field. The games are enriched with multimedia and AR resources, triggered through the recognition of AR markers distributed throughout the POIs. These AR experiences provide additional information regarding the present reality, reinforcing learning through observation and searching, and linking theoretical knowledge to direct exploration of the landscape. The educational settings in which the games were implemented varied according to each group's teaching context. Nevertheless, all implementations involved authentic learning environments, including school surroundings, urban spaces or community-based locations, in line with the Open Schooling principles underpinning the workshop.

3.3. Data Corpus

Data collection relied exclusively on documentary sources developed during the workshop and implementation process. This approach was appropriate because the study focused on the products and traces of teacher design, implementation and reflection. The primary analytical corpus included three types of documentary evidence: teacher-designed digital games, group implementation presentations and reflective artefacts, as presented in Table 1. Workshop training materials were used as contextual evidence of the conceptual and formative scaffolding provided during the workshop rather than as a separate source of participant evidence.

The three teacher-created games were "O Sal a 360°" [Salt at 360°] (see Appendix A for a detailed description of the game structure, route, and interdisciplinary questions), "Mário Sacramento e a cidade" [Mário Sacramento and the city], and "À descoberta da

cidade de Aveiro" [Discovering the city of Aveiro]. Together, these games included 14 POIs, 46 question blocks, 38 ARBooks and 8 augmented markers.

Table 1. Documentary data sources included in the qualitative analysis and their analytical functions.

Data Source	n	Description	Analytical Function
Teacher-designed EduCITY games	3	Mobile educational games created by teacher groups using the EduCITY platform	Evidence of pedagogical design decisions, including POIs, questions, resources, ARBooks, augmented markers and feedback
Group implementation presentations	3	Teacher-produced final presentations documenting implementation and incorporating student-related material, including comments, response summaries and satisfaction results where available	Evidence of implementation, iterative change cycles, perceived student engagement, constraints and group interpretation. Student-related material was treated as embedded documentary evidence rather than as an independently collected student dataset
Reflective artefacts	13	Ten individual reflections and three group reflections shared through Padlet and related workshop documentation	First-hand teacher evidence of professional learning related to technology knowledge, perceived challenges, framework integration and transfer to future practice

The group presentations documented how the games were implemented with students and included descriptions of game-based activities, graphical representations of student responses, student comments and satisfaction-related evidence where available, and teacher reflections on implementation. Student-related material was embedded in the teacher-produced implementation presentations and was not collected directly by the research team as a separate student dataset. It was therefore analyzed as documentary evidence of implementation and cannot be assumed to represent all students involved in the three implementations. The reflective artefacts included 10 individual reflections and three group reflections, capturing participants' perceptions of pedagogical integration, professional learning and future application. These reflections constituted first-hand teacher evidence within the qualitative corpus.

3.4. Data Analysis

Data were analyzed through qualitative thematic analysis supported by MAXQDA Tailwind [31]. The software was used to organize the data corpus, structure the document system, code the materials, retrieve coded segments, produce code-frequency outputs, generate case-by-code matrices and maintain an auditable analytical trail. MAXQDA Tailwind [31] was therefore used as a tool for systematic data management, coding traceability and cross-case comparison. Analytical interpretation remained the responsibility of the research team.

The analytical process combined deductive and inductive procedures. The three top-level analytical codes were defined deductively from the research questions: teacher design capacity and professional learning (RQ1); integration of STEAM, UDL and Open Schooling (RQ2); and challenges and opportunities in design and implementation (RQ3). The conceptual foundations of the study further informed the initial operationalization of these categories. Subcodes were subsequently developed and refined through a combined deductive-inductive process, in which conceptually anticipated categories were examined against recurrent patterns in the documentary corpus. This process allowed the code system to incorporate evidence related, for example, to iterative design and refinement,

transfer to future practice, technological and pedagogical constraints, and assessment and data-validity concerns. The resulting code system is presented in Table 2.

Table 2. Research question-based analytical code system.

Research Question (RQ)	Analytical Focus	Subcodes	Analytical Meaning
RQ1	Teacher design capacity and professional learning	Teacher authorship and resource creation; iterative design and refinement; digital pedagogical competence; sustainability-oriented design capacity	Evidence of teacher authorship and resource creation, iterative development and refinement, pedagogical use of digital technologies, and sustainability-oriented design decisions
RQ2	Integration of STEAM, UDL, and Open Schooling	STEAM integration; UDL-compatible design; Open Schooling and place-based learning; integrated framework alignment	Evidence of interdisciplinary articulation, UDL-compatible design features, meaningful connections with real places and community contexts, and articulation across the pedagogical frameworks
RQ3	Challenges and opportunities in design and implementation	Student engagement, collaboration and autonomy; opportunities for transfer and future practice; technological constraints; pedagogical and organizational constraints; assessment and data-validity concerns	Evidence of perceived student engagement, collaboration and autonomy; opportunities for reuse or transfer; and technological, pedagogical, organizational, assessment-related and data-validity challenges

The codebook documented the meaning of each subcode, together with inclusion and exclusion criteria and indicative forms of evidence. Coding revisions were incorporated into the evolving code system and documented through the analytical audit trail, which recorded the progression from the research questions and document grouping to case definition, code-tree development, coding, matrix generation and thematic interpretation.

This initial framework enabled the researchers to examine how the key principles of the workshop were reflected in the teacher-designed resources, and implementation and reflective artefacts. Inductive engagement with the corpus was used to refine rather than replace the RQ-based analytical structure, allowing recurrent patterns to be incorporated while maintaining traceability between the research questions, codes and evidence. The analysis was informed by established approaches to thematic analysis in qualitative research [32]. The final code system therefore comprised three top-level codes and 13 subcodes.

The analysis followed an iterative process. The data corpus was imported into MAXQDA [31] and organized by document group: game artefacts, implementation presentations, individual reflections, group reflections and training materials. The three games were treated as cases to enable comparison across teacher groups. The five-researcher team coded the materials collaboratively, using the RQ-based code system and refining coding decisions through discussion. When coding interpretations differed, the relevant segments were reviewed against the code definitions and discussed collectively until a consensual coding decision was reached. Coding consistency was therefore addressed through collaborative review and consensus. No formal statistical intercoder-reliability coefficient was calculated. Coded segments were retrieved and reviewed to identify thematic patterns, illustrative excerpts and relationships between codes. MAXQDA [31] outputs, including code frequencies, code matrices, co-occurrence tables and case summaries, were used to support the organization of the results.

Coded-reference counts were used as indicators of thematic density and analytical salience. They were not interpreted as inferential statistics or as measures of effect size. Instead, they supported the identification of more and less prominent themes within the qualitative corpus. Portuguese excerpts were preserved as primary evidence during coding. Quotations selected for presentation in the article were translated into English for publication, while the original Portuguese wording was retained in the analytical records to enable checking against the primary evidence.

3.5. Trustworthiness, Ethics and Researcher Reflexivity

Trustworthiness was addressed through credibility, transferability, dependability and confirmability, following established criteria for qualitative inquiry [29,30]. Credibility was strengthened through data triangulation and analyst triangulation, as the study combined game artefacts, implementation presentations and individual and group reflections. The involvement of five researchers further supported credibility by enabling collaborative interpretation and peer validation of coding decisions.

Transferability was supported through thick description of the research context, including the structure of the workshop, the participants' disciplinary backgrounds, the pedagogical frameworks mobilized, the EduCITY environment and the characteristics of the teacher-created games. Given the voluntary self-enrolment of participants and the bounded context of a single professional development workshop, transferability depends on the degree of similarity between this context and other teacher professional development settings rather than on statistical generalizability. Dependability was addressed through a transparent audit trail documenting the progression from research questions to code system, document grouping, case comparison, coding, matrix generation and thematic interpretation. Confirmability was reinforced through systematic coding procedures, collaborative discussion and reflexive attention to the researchers' role in the training context.

The study followed ethical principles for educational research. Participation in the research component was voluntary and based on informed consent. Only data from consenting participants were included in the analysis. Workshop artefacts were anonymized before analysis and reporting, and identifying information related to teachers, students, schools and specific classroom contexts was removed or generalized where necessary. Student-related evidence included in the group presentations was treated only as documentary and aggregated evidence of implementation. Student-related evidence included in the group presentations was treated only as documentary evidence embedded in teacher-produced implementation materials, rather than as an independently collected student dataset. It was interpreted cautiously as evidence of perceived engagement and perceived learning, not as causal evidence of learning gains or as necessarily representative of all students involved in the implementations.

The researchers acknowledge their proximity to the training context and to the pedagogical frameworks underpinning the workshop. This positioning provided in-depth contextual understanding but also required reflexive attention to possible interpretive bias. To address this, coding decisions were discussed collectively, interpretations were checked against retrieved documentary evidence, and claims were calibrated according to the strength of the data. Interpretive consistency was further supported through the shared codebook, explicit inclusion and exclusion criteria, collaborative consensus coding and the analytical audit trail linking coding decisions to the documentary evidence. This was particularly important in relation to three interpretive boundaries: coded-reference counts were treated as indicators of thematic density, not as statistical measures; UDL was reported as UDL-compatible or partially operationalized design, rather than as full

UDL implementation; and student evidence was interpreted as perceived engagement and perceived learning, not as objective measurement of learning outcomes.

4. Findings

The findings are organized around the main themes identified through the qualitative thematic analysis of the teacher-created EduCITY games, implementation presentations, and individual and group reflections. The analysis generated 594 coded references across the three teacher-created mobile games and associated documentary evidence. These coded references are used as indicators of thematic density and analytical salience, not as inferential statistics.

The thematic structure of the findings is presented in Table 3.

Table 3. Main themes, subthemes and interpretive focus.

Theme	Subthemes	Main Evidence Sources	Interpretive Focus
Teacher authorship and mobile learning design capacity	Resource creation; digital pedagogical competence; iterative refinement; sustainability-oriented design	Games (see example in Appendix A); presentations; individual and group reflections	Teacher authorship was evidenced through the creation and iterative refinement of situated digital resources
Integration of STEAM, UDL and Open Schooling	Interdisciplinarity; place-based learning; multimodal design; integrated framework alignment	Games; presentations; reflections	Integration was strongest when organized around a coherent local phenomenon
Pedagogical benefits and student engagement	Motivation; collaboration; autonomy; practical learning; situated observation	Presentations; student comments; reflections	Mobile game-based learning was perceived as meaningful, practical and engaging
Technological and organizational barriers	App access; iOS optimization; AR difficulties; game restarts; implementation constraints	Presentations; reflections; student comments	Technical reliability affected participation, inclusion and data validity
Transfer and future professional practice	Reuse of resources; future classroom application; design confidence; need for further refinement	Individual and group reflections	The workshop opened opportunities for sustained professional learning, but deeper support is needed

Student-related evidence was available only through the teacher-produced implementation presentations and varied in detail across the three cases. In "Mário Sacramento and the City", the presentation documented implementation with 28 students from an 8th-grade class, organized into six groups, and included questionnaire results and four illustrative student comments. In "Discovering the city of Aveiro", the presentation documented an 11th-grade class organized into six groups and reported a mean motivation rating of 4.4 on a five-point scale but did not specify the total number of students. In "Salt at 360°", the presentation referred to one class organized into four teams and included a student satisfaction questionnaire but did not report the total number of students. The "Mário Sacramento and the City" and "Salt at 360°" presentations explicitly identified questionnaire-based student feedback; however, the available documentary record does not specify whether all written comments were reproduced, or the criteria used to select the verbatim excerpts presented. Accordingly, student comments were treated as illustrative

teacher-documented evidence and were not assumed to represent all students involved in the implementations.

Overall, the findings show that teachers engaged with educational technology in an authorial and design-oriented role, creating and refining situated digital resources rather than using the platform only as end users. However, the evidence also shows that the integration of sustainability, STEAM, UDL, and Open Schooling was not equally explicit across all teacher productions.

4.1. Teacher Authorship and Mobile Learning Design Capacity

The first major theme concerns the development of teachers' capacity to design mobile game-based learning experiences for sustainability. The evidence indicates that the workshop positioned teachers not merely as users of an educational platform, but as authors of digital, place-based and curriculum-oriented resources. This was the most prominent theme in the analysis. RQ1 generated 220 coded references, with stronger evidence relating to teacher authorship and resource creation, digital pedagogical competence, iterative design and refinement, and sustainability-oriented design capacity. These patterns suggest that the main outcome of the workshop was teachers' ability to create and structure mobile learning resources, while sustainability-oriented design emerged with varying degrees of explicitness across the three cases.

The three games materialized pedagogical decisions about places, tasks, resources, feedback, and student interaction. In "Salt at 360°", the evidence points to a stronger sustainability-oriented design. The game connected salt production, the saltpans, local heritage, ecosystems, science and mathematics. In their group implementation presentation, the teachers explicitly referred to the "creation of original, creative and pedagogical digital educational resources" and to the "natural interaction with ARBooks and AR", suggesting that teachers combined local sustainability-related content with digital resources and augmented features.

This case provides the clearest evidence of a mobile learning experience in which sustainability was not treated as an additional topic, but as the organizing phenomenon of the game. Teacher-documented student evidence further reinforced this interpretation through the illustrative comment "I learned about salt/saltpans".

In "Mário Sacramento and the City", the evidence emphasized the use of the school and the surrounding city as an exploratory learning environment. A teacher-documented student comment describing how the activity allowed students to "go around the school and the city looking for clues" illustrates how the game extended learning beyond the classroom and required teachers to organize a structured route through local spaces, as presented in Figure 1.

This interpretation is reinforced by the teachers' final group reflection, which states that students "applied and related scientific content from different subjects". The same presentation provides direct teacher evidence about the resource-development process: the teachers attributed the improvements made to the game to "support from the trainers during game development", "consultation of tutorials and information sharing during the training sessions", and "tests carried out with the game application". In this case, teacher authorship was expressed through the transformation of school identity, local memory, and civic learning into a mobile learning path.

In "Discovering the city of Aveiro", the evidence was particularly strong in relation to refinement and redesign. In their final implementation presentation, the teachers documented specific changes such as "feedback was added to question 1", "the existing ARBook was improved", and "the feedback for question 3 was improved". These segments show that teachers did not simply produce a final digital artefact, but revised the resource

after preliminary trialing, discussion or implementation. This suggests that the workshop supported an iterative design cycle, in which feedback, technological constraints, and pedagogical coherence became part of the professional learning process.

Figure 1. "Ovos Moles" Monument, "Mário Sacramento and the City" game.

At the case level, "Salt at 360°" showed the strongest thematic density for teacher authorship and design capacity, followed by "Discovering the city of Aveiro" and "Mário Sacramento and the city". These differences should, however, be interpreted qualitatively rather than quantitatively.

Each game revealed a distinct profile of teacher authorship. "Salt at 360°" presented the most coherent connection between local heritage, sustainability and mobile game-based learning; "Mário Sacramento and the city" displayed strong contextual and civic design, although sustainability remained comparatively implicit; and "Discovering the city of Aveiro" showed strong iterative refinement and digital pedagogical competence.

4.2. Integration of STEAM, UDL and Open Schooling

The second theme concerns the integration of STEAM, UDL and Open Schooling principles into the resources developed by teachers. RQ2 generated 210 coded references, with the strongest evidence relating to Open Schooling and place-based learning. Other relevant dimensions included STEAM integration, UDL-compatible design and alignment with the integrated framework.

The findings show that Open Schooling was the most consistent dimension across the three games. Teachers mobilized school surroundings, urban spaces, heritage sites and saltpans as pedagogical resources. These places were not used merely as backdrops; they

shaped the design of the learning tasks and created opportunities for students to connect curricular knowledge with local environments and community-based challenges.

In "Salt at 360°" (see Appendix A), integration was more coherent and thematically grounded. Salt production and the saltpans functioned as a shared local phenomenon through which science, mathematics, heritage, environment, and sustainability could be connected. The segment from teacher/group evidence "seamless integration across different academic disciplines" supports this interpretation. This alignment was also visible in the game's opening framing, which invited students to look at traditional salt production "from a comprehensive, 360-degree perspective". In this case, STEAM, Open Schooling and sustainability converged around a common phenomenon, rather than appearing as parallel dimensions.

In "Mário Sacramento and the city", integration was broad and multidisciplinary, involving History, Geography, Sciences, Music and Citizenship. Teacher/group evidence from the final reflection described this articulation as students having "applied and related scientific content from different subjects". However, the evidence suggests that several tasks remained relatively discipline-specific. In this case, STEAM appeared more as curricular juxtaposition than as fully integrated problem-based design. Even so, teacher-documented student evidence such as "it was particularly helpful in guiding me and helping me to observe my surroundings" indicates that the route supported spatial orientation, observation and situated engagement with the local environment, as presented in Figure 2.

Figure 2. Mário Sacramento's memorial tile panel, "Mário Sacramento and the City" game.

In "Discovering the city of Aveiro", integration was more functional, since the city was used as a learning laboratory for mobility, geometry, urban sustainability, and environmental interpretation. Student evidence such as "the layout of buildings using mathematical concepts" illustrates how urban space was connected to geometrical reasoning. Game-artefact evidence also framed walking as "the most sustainable form of mobility, free of charge and with health benefits", reinforcing the connection between mobility, everyday urban space and sustainability. This case therefore showed a stronger articulation between curricular knowledge and everyday urban learning, particularly through tasks related to mobility, the built environment, and sustainability.

UDL was mainly visible through multiple means of representation and engagement. Teachers used images, videos, ARBooks, AR, maps, game challenges, feedback, and collaborative activities to diversify students' access to content and forms of participation. Student comments such as "a dynamic experience that made learning more fun and motivating" and "to learn in a more practical way" support the interpretation that these resources created varied and engaging learning opportunities.

However, the evidence does not support a claim for full UDL implementation. It is stronger in relation to UDL-compatible design features than to the systematic diversification of learner action and expression, accessibility pathways or individualized supports. In other words, the games incorporated multimodal and motivational features aligned with UDL but did not consistently demonstrate proactive planning for the full range of learner variability.

The relationship between the frameworks is therefore interpretive, rather than merely descriptive. STEAM became stronger when linked to real places, while Open Schooling became more pedagogically meaningful when those places were transformed into learning problems. UDL was visible through multimodal resources and engagement strategies but required further development to operate as a fully embedded design principle. Overall, the strongest forms of integration emerged when teachers selected a coherent local phenomenon capable of connecting disciplines, places, technologies and sustainability-related meanings.

4.3. Pedagogical Benefits and Perceived Student Engagement

The third theme concerns the pedagogical benefits perceived during implementation, particularly student engagement, collaboration, autonomy, and practical learning. RQ3 generated 164 coded references, with the strongest evidence relating to student engagement, collaboration, and autonomy. Other relevant subthemes included technological constraints, opportunities for transfer to future practice, pedagogical and organizational constraints, and concerns related to assessment and data validity.

Across the cases, teacher-produced implementation presentations and the student comments embedded within them indicated opportunities for motivation, teamwork, practical learning, and active participation. Teacher-documented student evidence such as "improve our ability to work as a team", together with teacher/group evidence such as "enhanced collaboration and teamwork", suggests that the mobile games supported peer interaction and cooperative problem-solving. In "Salt at 360°", the teacher/group evidence pointed to "a positive impact on students' independence", thus indicating that mobile game-based learning may also support more active learner roles, particularly when students navigate places, tasks and digital resources through the app (see Appendix B).

The evidence also suggests that students perceived learning as more meaningful when it was connected to real places. This was reflected in students' comments about "guidance and observation of the surrounding environment", learning through practical activity "in a more practical way", and gaining knowledge about salt and the saltpans as in this student's direct evidence "I learned about salt/saltpan". These findings are pedagogically relevant because they show that teacher-designed mobile games can support learning experiences that students recognize as dynamic, situated, and useful.

These findings should nevertheless be interpreted with caution, since the data corpus supports claims about perceived engagement, perceived learning and pedagogical relevance, but not causal claims about learning gains or competence development. The available evidence includes student comments, teacher reflections, implementation presentations, and game printables, rather than independent pre-post measures of student learning. The pedagogical benefits identified in this study should therefore be understood as perceived and situated outcomes of the implementation process.

4.4. Technological and Organisational Barriers

The fourth theme concerns technological and organizational barriers affecting the design and implementation of the mobile learning experiences. The main challenges were technological, particularly in "Discovering the city of Aveiro", where the evidence referred

to operating system compatibility and AR access. Teacher/group evidence such as "the app is not optimized for the iOS system" and "difficulty opening the AR" suggests that technical issues shaped the implementation experience as well.

In "Salt at 360°", the teacher-documented student comment "It was difficult to log into the app" points to access difficulties that may have constrained participation and inclusion. These are not minor technical issues. In mobile game-based learning, technological reliability shapes the conditions in which students can participate, collaborate, access content and complete the learning route.

The analysis also identified a data-validity concern related to game restarts. The observation that, when play resumes, students may already possess relevant information points to a specific methodological issue: if a game is restarted after feedback has been received, later responses may be influenced by prior exposure to correct answers. This was explicitly noted in teacher/group evidence from "Discovering the city of Aveiro": "when the game is restarted, the player already has information that gives them the correct answers". This limits the interpretability of game scores and suggests that gameplay data should be analyzed with caution.

These technological and organizational barriers matter because they affect both pedagogy and research interpretation. A mobile game may be well designed from a curricular perspective, but its educational value depends on whether students can access the app, open augmented resources, follow the physical path and complete tasks under stable conditions. Technical interruptions may also compromise the validity of data generated during gameplay. In this sense, technology functions both as a pedagogical mediator and as a potential constraint.

4.5. Transfer and Future Professional Practice

The final theme concerns the opportunities created by the workshop for future professional practice. The evidence suggests that teachers developed not only specific digital resources, but also design knowledge that could be transferred to other educational contexts. Individual and group reflections showed that teachers recognized the potential of mobile game-based learning for interdisciplinary work, outdoor learning, sustainability education and student engagement. In the final group reflection for "Mário Sacramento and the City", teachers described the activity as "an opportunity to diversify strategies and motivate students for learning". In the final presentation for "Discovering the city of Aveiro", teachers reported that students had highlighted "the importance of continuing to integrate this type of game into pedagogical practices".

The workshop created a professional learning context in which teachers could design, test, revise and reflect on their own resources. This process is important because it links professional development with pedagogical agency. Rather than working with ready-made digital materials, teachers were supported in making decisions about content, places, resources, questions, feedback and implementation strategies. This is visible in the teachers' final implementation presentation for "Discovering the city of Aveiro", where they referred to having "invested in the resources" and carried out "several corrections and tests before implementation with the class".

At the same time, the findings show that transfer to future practice depends on several conditions: time for teachers to design and test resources, technical support for reliable implementation, clearer criteria for UDL integration, and opportunities to reflect on assessment and data validity. Teacher/group evidence from "Discovering the city of Aveiro" explicitly stated that "based on the results and on students' opinions, it is possible to establish some paths to improve future EduCITY implementations". The workshop therefore provided a productive starting point for teacher professional learning, while

also showing that sustained support is needed for these practices to become embedded in regular teaching.

Overall, the findings indicate that the articulation between OpenUS4ALL and EduCITY created meaningful opportunities for teacher authorship, interdisciplinary design, place-based learning and student engagement. The strongest evidence relates to teacher design capacity, Open Schooling, STEAM-oriented interdisciplinarity and perceived student engagement. At the same time, the findings show that UDL was mainly expressed through multimodal and motivational features, while technological reliability, accessibility and data-validity issues remained important constraints.

5. Discussion

This study examined how an accredited teacher professional development workshop supported the design and implementation of mobile game-based learning experiences for sustainability, within an integrated framework of STEAM, UDL and Open Schooling. The findings address a relevant gap between the theoretical potential of these frameworks and the professional knowledge required by teachers to implement them effectively: although these frameworks are widely valued in contemporary education, there is still limited empirical evidence on how teachers can operationalize them together in tangible digital resources. The discussion therefore considers how teacher digital competence, pedagogical design, technology-enhanced learning and sustainability education intersect within this bounded professional development context.

5.1. Interpretation of the Findings

The first major interpretation is that the workshop supported teachers' engagement with educational technology in an authorial and design-oriented role. Teachers did not merely learn to use EduCITY as a technical platform; they designed routes, selected places, created questions, integrated multimedia and augmented resources, produced feedback and reflected on implementation. This suggests that the workshop operated as a design-oriented professional development environment, in which digital competence was expressed through situated pedagogical production and design decision-making.

This is significant because the educational value of mobile game-based learning depends not only on access to technology, but also on the quality of pedagogical design. The evidence indicates that professional learning extended beyond technical familiarization, as teachers engaged with the platform as a space for pedagogical authorship and digital resource creation. This also suggests that teacher professional development in mobile game-based learning should be understood as a process of design participation, not merely as training in platform use. In this study, professional learning became visible through the production, testing and refinement of concrete educational resources. The evidence therefore documents teacher authorship as a mode of engagement within the workshop, rather than establishing a measured transition from a prior exclusively user-oriented role.

Why this authorial engagement emerged may be explained by the combination of several characteristics of the workshop rather than by access to the EduCITY platform alone. Teachers worked in interdisciplinary groups throughout design, implementation and reflection; they were required to produce an authentic digital resource connected to their own curricular and local contexts; and they directly authored, tested and revised the games before and after implementation. The documentary evidence also identifies trainer support, consultation of tutorials, information sharing during the training sessions and testing with the EduCITY application as factors that supported improvements to the resources. Together, these conditions created repeated opportunities to move between ped-

agogical intention, digital production, implementation feedback and resource refinement. Within this bounded case, teacher authorship therefore appears to have been supported by responsibility for consequential design decisions combined with collaborative, situated and iterative opportunities to test and reconsider those decisions.

The second major interpretation is that the integration of STEAM, UDL and Open Schooling was strongest when the game was organized around a coherent local phenomenon. "Salt at 360°" offered the clearest example, as salt production and the saltpans provided a shared context for connecting science, mathematics, heritage, environment and sustainability. This suggests that interdisciplinarity became more meaningful when disciplines were not simply placed side by side, but articulated through a common problem, place or phenomenon.

The third interpretation concerns UDL. The findings suggest the presence of UDL-compatible features, especially in relation to multiple means of representation and engagement, but they do not support a claim of full UDL implementation. This distinction matters because multimedia, AR and playful interaction do not, by themselves, make a resource universally designed. UDL requires intentional planning for learner variability, including flexible ways of accessing information, participating in activities and demonstrating understanding. This distinction is important because it prevents the overinterpretation of multimodality as inclusivity. The findings indicate that UDL was present as a design orientation, but not yet as a fully systematic design framework.

The fourth interpretation concerns technology as both mediator and constraint. EduCITY enabled teachers to design place-based, multimodal and game-based learning experiences, but its implementation was also affected by issues related to app access, iOS optimization, AR and game restarts. These difficulties are pedagogically relevant because they shaped participation, inclusion, classroom management and the reliability of data generated during gameplay. This means that technical preparation should be considered part of pedagogical design, particularly when mobile games generate data that may later be used for reflection, assessment or research purposes.

Finally, the findings suggest that student engagement should be interpreted as perceived engagement and perceived learning, not as causal evidence of learning gains. Teacher-produced implementation materials and the student comments embedded within them indicated motivation, collaboration, autonomy and practical learning. However, the study did not include independent measures of learning outcomes. Therefore, the strongest contribution of the study lies in understanding teacher professional learning and design capacity, rather than demonstrating measurable student achievement.

5.2. Connection to Literature

The findings are consistent with research on mobile learning and digital game-based learning, which shows how these environments can support engagement, contextualized learning, active participation and situated educational experiences [1,2,4]. This study extends that literature by shifting attention from students' use of mobile games to teachers' design processes, thereby contributing a professional development perspective to mobile game-based learning research. In this sense, the findings support an interpretation of teacher digital competence that extends beyond operational technology use to include the capacity to author, contextualize, test, refine and implement digital educational resources. This interpretation complements recent empirical evidence showing relationships between digital professional development, professional learning communities and teachers' integration of digital technologies into instruction [27], as well as evidence from secondary education that digitally supported professional development can engage teachers as active and reflective participants in professional learning [28].

The findings also resonate with literature on sustainability education and serious games, which suggests that digital game-based approaches can make sustainability issues more tangible and engaging when connected to authentic, real-world contexts [3,5]. At the same time, the study adds nuance to this argument. Sustainability-oriented learning does not emerge simply from outdoor activity or mobile technology; it depends on how the local context is pedagogically framed. A route may be place-based without being strongly sustainability-oriented. Sustainability becomes more central when the local phenomenon itself organizes the learning experience, as occurred in "Salt at 360°".

The findings are also consistent with literature on STEAM and integrated STEM education, which emphasizes real-world problems, interdisciplinary knowledge mobilization, collaboration and student-centered inquiry [6–13]. However, the study shows that STEAM integration in teacher-designed mobile games requires more than bringing several disciplines together. It becomes stronger when teachers organize the learning experience around a shared phenomenon that calls for multiple disciplinary perspectives.

Regarding Open Schooling, the findings reinforce the view that schools can become more outward-facing when curricular learning is linked to community spaces, local challenges, external stakeholders and real-life issues [11,17–19]. In this respect, EduCITY offers a relevant infrastructure for location-based learning, combining routes, POIs, augmented markers, ARBooks and sustainability-oriented mobile learning tasks [4,20]. At the same time, the uneven integration observed across the three cases is consistent with recent empirical research showing that Open Schooling for sustainability can challenge established teaching practices and requires teachers to translate authentic problems, collaboration and external contexts into workable pedagogical designs [26]. In the present study, therefore, the use of an outdoor or urban setting was not sufficient in itself; Open Schooling became pedagogically stronger when the place was transformed into a meaningful curricular problem or learning context.

Regarding UDL, the findings confirm the existing literature. They support the view that multimodal resources, varied forms of engagement and flexible access to content can contribute to more inclusive learning environments [7,14–16]. At the same time, they suggest that UDL may be narrowed to multimedia use when teachers are not explicitly supported in designing for learner variability. This adds an important practical insight to research on teacher-designed technology-enhanced learning: a resource may be engaging and multimodal without being fully inclusive.

5.3. Theoretical Implications

The findings offer three main theoretical contributions. First, in relation to teacher digital competence and professional development, the study supports an understanding of digital competence that is not limited to operational technology use. Within this case, it was expressed through teachers' capacity to author, contextualize, combine, test, refine and implement digital educational resources. Teacher design capacity can therefore be understood as a pedagogical expression of digital competence, in which professional agency becomes visible through decisions about places, tasks, questions, resources, feedback and technological mediation.

Second, in relation to technology-enhanced learning and mobile game-based learning, the findings support a relational rather than technology-centered interpretation. The educational affordances of the platform became meaningful through their alignment with curricular objectives, task design, place, collaboration, feedback and implementation conditions. Conversely, technical difficulties with access, AR or game restarts demonstrate that technology can simultaneously enable and constrain pedagogical participation and the validity of implementation data.

Third, in relation to sustainability education, the findings indicate that place-based or outdoor activity is not intrinsically sustainability-oriented. Sustainability became more explicit when a local phenomenon was used to organize disciplinary knowledge, community relevance and sustainability-related meanings. From this perspective, STEAM, UDL and Open Schooling operate as complementary but non-equivalent design lenses: STEAM supports interdisciplinary articulation, UDL foregrounds learner variability and accessibility, and Open Schooling connects curricular learning with authentic places and community contexts. Their pedagogical contribution depends on how deliberately these dimensions are articulated in the design of the learning experience.

Therefore, the theoretical value of mobile learning should be located not in the device or platform itself, but in the relationship between design, context, pedagogy and implementation conditions. This relational interpretation is particularly relevant for sustainability education, where educational value depends on how learners are invited to interpret places, problems and practices, rather than on the mere presence of mobile or augmented technologies.

5.4. Practical and Educational Implications

These results have implications for teachers, curriculum design, teacher training, policy-making and technology integration.

For teachers, the study suggests that mobile game-based learning gains educational value when it is carefully designed around authentic places and real-world challenges. Games should therefore not be treated as engaging add-ons, but as structured learning environments in which place, content, interaction and feedback are pedagogically aligned.

For curriculum design, the findings indicate that local contexts can function as curricular resources. Surrounding environments, heritage sites and ecological contexts may support interdisciplinary learning when connected to clear learning objectives and meaningful tasks. This is particularly relevant for education for sustainability, where students are expected to interpret complex socio-environmental issues in context.

For teacher training, the study highlights the value of design-based professional development. Teachers need opportunities to design, implement, evaluate and refine resources, rather than only receive theoretical input or technical demonstrations. In this study, the combination of interdisciplinary collaboration, direct authoring in EduCITY, trainer scaffolding, tutorials and information sharing, iterative testing, implementation with students and subsequent reflection appears to have supported teacher authorship and digital pedagogical competence. Teacher training should also include explicit scaffolding for UDL-informed design, so that multimodal resources are complemented by planned options for learner access, participation and expression.

For policy-making, the findings suggest that innovation in digital education requires sustained conditions, including time for collaborative design, access to reliable infrastructure, institutional support and recognition of teacher authorship. Policies that promote digital transformation without addressing these conditions risk overestimating the impact of technology itself.

For technology integration, the study shows that technical preparation should be understood as part of pedagogical preparation. Device testing, operating system compatibility, AR checks, login procedures, offline or fallback strategies and restart protocols are not secondary details. They are necessary conditions for participation, inclusion, and the reliable interpretation of implementation data.

For assessment and learning analytics, the findings suggest that gameplay data should be interpreted cautiously when technical interruptions, repeated attempts or restarts may affect response patterns. Future implementations should therefore define clear proto-

cols for restarting games, recording incidents and distinguishing learning support from evaluative data.

5.5. Limitations

The study draws on a small and situated corpus, composed of three teacher-created games, and the documentary evidence associated with a single professional development workshop involving 13 in-service teachers. Its purpose is therefore not to support statistical generalization, but to offer an analytically transferable account of how teachers engaged with the design of educational games in a specific training context. Participation in the workshop resulted from voluntary self-enrolment, which created a self-selected cohort and may limit transferability to teacher populations with different motivations, interests or professional contexts. In addition, no systematic baseline information was collected on participants' prior experience with digital technologies, mobile learning or digital game-based learning. Consequently, the study cannot determine the extent to which previous technological or pedagogical experience may have shaped teachers' engagement with the workshop or their design practices. The documentary nature of the evidence is also important. The artefacts produced during the training and implementation process are well suited to examining teacher design capacity and professional learning, but they cannot fully capture the complexity of all classroom interactions as they unfolded in practice.

The researchers' double involvement in the workshop, as trainers and as researchers, also needs to be acknowledged. This proximity to the training context made reflexive attention to possible interpretive bias particularly important. The study addressed this through systematic coding, triangulation across sources, and the maintenance of an audit trail. Nevertheless, researcher positionality remains part of the interpretive context in which the analysis was developed. Similarly, coded-reference counts were used to signal thematic density and analytical salience, not to measure effect size, statistical significance, or frequency in a wider population.

Claims concerning student learning must also be read with caution. Student-related evidence was embedded in teacher-produced implementation presentations rather than collected by the research team as an independent student dataset, and the available documentary record does not establish that the illustrative student comments represent all students involved in the implementations. The evidence therefore supports discussion of engagement, collaboration and perceived learning, but not causal claims about learning outcomes [33]. In addition, the workshop took place within a limited timeframe, which restricted the opportunities for teachers to refine their resources through repeated cycles of classroom implementation.

Future research should address these limitations through studies involving multiple professional development cohorts and larger, more diverse groups of teachers across different disciplinary and institutional contexts. Baseline characterization of teachers' prior experience with digital technologies, mobile learning and game-based learning would allow professional learning trajectories to be interpreted more precisely. Comparative and longitudinal designs could examine whether and how teacher design capacity is transferred into subsequent classroom practice, while direct classroom observation and independently collected student data could provide stronger evidence concerning implementation processes and learning outcomes. Further studies should also examine how UDL can be operationalized more systematically in mobile and outdoor game-based learning, including accessibility and learner variability, and should investigate the usability, technological reliability and data-validity conditions of these environments across repeated implementation cycles. A further research direction concerns teacher professional development for the critical and pedagogically grounded use of generative Artificial Intelligence (AI)

in the design of mobile games and digital educational resources. Future studies could examine how generative AI supports teachers in authoring, adapting, validating and refining questions, feedback, multimedia resources and game-based learning activities, while also addressing issues of accuracy, transparency, authorship, accessibility and responsible use. Design-based research may be particularly useful for examining how teacher-created resources and professional development structures evolve through successive cycles of design, implementation, evaluation and refinement.

6. Conclusions

This study examined how an accredited teacher professional development workshop supported teachers in designing and implementing mobile game-based learning experiences for sustainability through the integration of STEAM, UDL and Open Schooling principles. The findings show that the workshop created meaningful opportunities for teacher authorship, interdisciplinary design, place-based learning and perceived student engagement.

The study emphasizes that teacher professional development for mobile game-based learning extends beyond technical training. Teachers need structured opportunities to design, test, evaluate and refine learning environments that connect curricular goals, community contexts, student engagement, digital resources and sustainability-related challenges. In this study, the strongest evidence concerned teachers' ability to create situated digital resources and to transform local places into learning environments.

The study also shows that integration between STEAM, UDL and Open Schooling is possible, but uneven. Integration was strongest when the learning experience was organized around a coherent local phenomenon, as in the case of "Salt at 360°". Open Schooling was strongly visible through the use of real places and community-connected learning contexts. STEAM was present through interdisciplinary tasks, although sometimes as curricular juxtaposition rather than deep integration.

UDL was visible mainly through multimodal and motivational features but was less systematically operationalized in relation to learner variability, accessibility and multiple forms of action and expression.

The findings also highlight practical conditions for teacher professional development and technology integration. Professional development should provide sufficient time and support for teachers to design, test, implement, evaluate and refine mobile learning resources, while incorporating explicit design criteria for STEAM integration, UDL, Open Schooling, sustainability education and data validity. Technical preparation should also be understood as part of pedagogical planning, particularly when mobile technologies, AR and outdoor learning are involved. This is especially relevant when gameplay data are used for reflection, assessment or research, since technical interruptions, repeated attempts or game restarts may affect the interpretation of students' responses.

Future research should examine similar training models across larger and more diverse teacher groups, include direct classroom observation, and incorporate more robust evidence of student learning. Baseline characterization of teachers' prior experience with digital technologies, mobile learning and game-based learning would also support more precise interpretation of professional learning trajectories. Longitudinal studies would also help clarify how teachers transfer mobile game-based learning design capacity into future practice. Further research should also investigate how UDL can be more systematically embedded in mobile, outdoor, and game-based learning environments. An additional direction concerns teacher professional development for the critical and pedagogically grounded use of generative AI in the authoring, adaptation, validation and refinement of mobile games and digital educational resources, including questions, feedback and multimedia resources.

In conclusion, the articulation between OpenUS4ALL and EduCITY provided a productive professional development context for teacher authorship of interdisciplinary, multimodal and place-based digital learning experiences. The study contributes to educational research on digital teacher professional development, by illustrating how design-oriented mobile game-based learning can make teacher digital competence visible through the authoring, contextualization, testing and refinement of sustainability-oriented educational resources. It also identifies pedagogical, technological and methodological conditions that shape the implementation of these experiences and the extent to which STEAM, UDL and Open Schooling can be meaningfully articulated in practice.

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Institutional Review Board Statement: The study was conducted in accordance with the ethical protocols established by the University of Aveiro and in compliance with the University of Aveiro's General Data Protection Regulation (GDPR) on 27 November 2024 and was approved by the Ethics Committee of the same institution (protocol code 1-CE/2025, 5 February 2025).

Informed Consent Statement: Participation was voluntary. Informed consent was obtained from all participants.

Data Availability Statement: The data generated and analyzed during the current study include teacher-created educational resources, implementation presentations, and reflective artefacts. Due to ethical and data protection considerations, the full dataset is not publicly available. Anonymized excerpts or derived analytical materials may be made available by the corresponding author upon reasonable request, subject to applicable ethical and legal restrictions.

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Abbreviations

The following abbreviations are used in this manuscript:

AR	Augmented Reality
ESD	Education for Sustainable Development
OpenUS4ALL	Open Universal STEAM for All
STEAM	Science, Technology, Engineering, Arts and Mathematics
UDL	Universal Design for Learning
SDG	Sustainable Development Goals
POI	Point of Interest
AI	Artificial Intelligence

Appendix A

Brief Description of the EduCITY Game "O Sal a 360"

This game is an example of an interdisciplinary educational activity developed collaboratively by a team of four teachers from different subject areas: Mathematics, Biology and Geology, Physics and Chemistry, and Geography.

The game was developed for secondary education students and aims to promote ESD through a comprehensive exploration of Aveiro's salt heritage and its environmental, cultural, scientific, and economic dimensions. Inspired by the Municipality of Aveiro's candidature of traditional salt production to intangible cultural heritage status, the game encourages participants to adopt a 360-degree perspective on one of the region's most emblematic activities. Through this approach, students are invited to reflect on the importance of preserving ancestral knowledge, valuing cultural identity, and promoting the sustainable use of natural resources.

The game begins at Rossio Square, one of the most emblematic public spaces in Aveiro, and follows a route through five POIs closely linked to the city's salt-making tradition and lagoon ecosystem. The route includes Rossio Square, the Troncalhada Saltworks Ecomuseum, the "Rotunda das Pirâmides", "Ostraveiro"—Aquaculture and Tourism, and "Marinha da Noeirinha". Along the way, participants explore the relationship between the "Ria de Aveiro" [Aveiro Lagoon], traditional salt production, aquaculture, biodiversity, tourism, and local heritage, gaining a holistic understanding of the ecological and socioeconomic importance of the lagoon system.

The game comprises 19 multiple-choice questions integrating content from Mathematics, Natural Sciences, Physics and Chemistry, and Geography. Activities challenge students to apply disciplinary knowledge to authentic contexts, addressing topics such as the Haff-Delta geomorphology of the "Ria de Aveiro", the evolution of "moliceiros" [traditional wooden boat unique to the Ria de Aveiro], salinity and evaporation processes, salt crystallization, chemical composition of minerals, biodiversity associated with salt marsh ecosystems, aquaculture practices, geometric concepts, trigonometry, scale representation, and volume calculations. The diversity of questions reflects the interdisciplinary nature of the activity. For example, some questions focus on the historical and geographical organization of the salt marshes, asking participants to identify how many groups of saltpans constituted the traditional salt-marsh map. Other questions require mathematical reasoning, such as calculating the volume of water contained in a saltpan tank based on its dimensions, depth, and filling level. The game also includes questions related to local products and biodiversity, where participants identify resources associated with the salt marsh ecosystem, including different types of salt and halophytic plants. In addition, environmental science questions challenge students to determine the optimal conditions for salt production by analyzing factors such as water salinity, temperature, and wind, thereby promoting an understanding of the natural processes involved in evaporation and

salt crystallization. Figure A1 illustrates four examples of these interdisciplinary questions. The first question focuses on historical and geographical knowledge, asking players to identify how many groups of saltpans ("marinhas") made up the salt-marsh map in the past. By observing the map and understanding its divisions, participants learn about the historical organization of the salt-production area. The second question is a mathematical challenge related to the operation of the saltpans. Players are given the dimensions and depth of a tank and must calculate the volume of water it contains when filled to 80% of its capacity. This type of question encourages the application of mathematical concepts, such as volume calculation, in a real-world context associated with salt production. The third question is centered on local products and natural resources. Using an image of a salt-marsh structure, players are asked to identify the products that are produced or harvested in that environment. These include different types of salt and halophytic plants, helping users learn about the economic and ecological value of the salt-marsh ecosystem. The fourth question addresses environmental science and the salt-production process. It asks participants to identify the optimal conditions for producing salt from seawater in saltpans, considering factors such as water salinity, temperature, and wind. Through this question, players gain a better understanding of the natural conditions that influence evaporation and salt crystallization. Together, these examples demonstrate how the game combines history, geography, mathematics, environmental science, and local heritage to create an engaging and educational learning experience about salt-marsh ecosystems and traditional salt production.

Figure A1. Examples of interdisciplinary questions.

Images, videos, and AR resources are integrated throughout the route to enrich observation and support inquiry-based learning. AR elements provide additional information on scientific concepts, salt production processes, cultural landmarks, and environmental features, strengthening the connection between classroom learning and field exploration. Several POIs use videos and AR markers to encourage participants to observe carefully, interpret evidence, and relate theoretical concepts to the surrounding landscape.

The game promotes interdisciplinary learning while fostering awareness of the ecological, cultural, and economic significance of Aveiro's salt-producing landscape. By combining heritage education, scientific inquiry, outdoor learning, and sustainability principles, "O Sal a 360°" encourages participants to value and safeguard the traditions, ecosystems, and

knowledge associated with salt production in the "Ria de Aveiro", while recognizing their relevance for a more sustainable future.

Appendix B

Results of the "O Sal a 360" Game Implementation

The game was implemented with three groups of secondary education students who completed the entire route and participated in all proposed activities. The results demonstrate a high level of engagement and successful completion of the educational challenges. Two groups achieved very similar performances, obtaining a score of 56 points, correctly answering 12 out of 16 questions. One of these groups accumulated an additional 5 points through the use of AR resources, while the other obtained the maximum AR score of 10 points. Their completion times were approximately 30 and 33 min, respectively. The third group completed the activity in a shorter time (20 min) but achieved a lower score of 26 points, with 7 correct answers out of 9 questions and 5 additional points obtained through AR interactions.

Overall, the results suggest that students were able to navigate the route autonomously following the app's instructions, engage with the digital resources, and apply knowledge from different disciplines in authentic learning contexts. The successful completion of the challenges and the frequent use of AR resources indicate that participants were motivated to explore the provided content and interact with the surrounding environment.

Teacher feedback was highly positive. The four teachers involved in the development and implementation of the activity highlighted the fluid integration of content from different subject areas, demonstrating the potential of game-based learning to support interdisciplinary approaches to Education for Sustainable Development. The game was perceived as an effective way of connecting concepts from Mathematics, Biology and Geology, Physics and Chemistry, and Geography within a meaningful real-world context.

Teachers also reported that students responded very positively to the original multimedia content, showing a high level of enthusiasm throughout the activity. According to the teachers, the game promoted the development of a wide range of cognitive skills, including observation, problem-solving, critical thinking, mathematical reasoning, and environmental interpretation. Furthermore, the collaborative nature of the activity strengthened teamwork and communication among participants, as students worked together to analyse information, discuss possible answers, and make decisions.

Another important outcome identified by the teachers was the positive impact on student autonomy. The route-based structure encouraged participants to manage their own learning process, navigate between POIs, and independently access information through mobile devices, AR resources, and field observations. The feedback was described as surprisingly positive, with teachers emphasizing the educational value of combining outdoor learning, local heritage, digital technologies, and sustainability themes. Overall, the implementation confirmed the effectiveness of the game as an engaging and interdisciplinary learning experience that fostered both curricular learning and awareness of the ecological, cultural, and economic significance of Aveiro's salt heritage.

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