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Mobile Augmented Reality Games Towards Smart Learning City Environments: Learning About Sustainability

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Abstract

This study explores the potential of mobile augmented reality games (MARGs) in promoting sustainability competencies within the context of a smart learning city environment. Anchored in the EduCITY project, which integrates location-based AR-enhanced games into an interactive mobile app, the research investigates how these tools support Education for Sustainable Development (ESD). Employing a mixed-methods approach, data were collected through the GreenComp-based Questionnaire (GCQuest) and anonymous gameplay logs generated by the app. Thematic analysis of 358 responses revealed four key learning domains: 'cultural awareness', 'environmental protection', 'sustainability awareness', and 'contextual knowledge'. Quantitative performance data from game logs highlighted substantial variation across games, with the highest performance found in those with more frequent AR integration and multiple iterative refinements. Participants engaging with AR-enhanced features (optional) outperformed others. This study provides empirical evidence for the use of MARGs to cultivate sustainability-related knowledge, skills, and attitudes, particularly when grounded in local realities and enhanced through thoughtful design. Beyond the EduCITY project, the study proposes a replicable model for assessing sustainability competencies, with implications for broader integration of AR across educational contexts in ESD. The paper concludes with a critical reflection on methodological limitations and suggests future directions, including adapting the GCQuest for use with younger learners in primary education.

Keywords: mobile learning; game-based learning; augmented reality; contextualized learning; smart city; learning environment; EduCITY; education for sustainability; sustainability competencies; mixed-methods study

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1. Introduction

Rapid technological progress and globalisation pose new challenges, contributing to growing complexity, uncertainty, and environmental degradation [1]. Although cities cover just 3% of Earth's surface, they consume 75% of resources and generate 70% of greenhouse gas emissions, thus threatening global sustainability [2]. Citizens need sustainability competencies to navigate complex challenges responsibly [3,4], considering environmental, economic, and social dimensions [5].

Education for Sustainable Development (ESD) empowers learners to make informed, responsible decisions for environmental integrity [3]. Effective approaches should

emphasise interactive, values-based, and transformative learning. Examples include the following: (1) Bucea-Manea-Țoniș et al. [6] highlight interactive teaching and technology's role in fostering active learning and sustainable behaviour; (2) Huang et al. [7] propose a values-based ESD framework to develop change-leaders; and (3) Macagno et al. [8] demonstrate that combining transformative learning with design thinking enhances student engagement and cultivates sustainability-oriented mindsets. These examples stress the need for action-oriented pedagogy, integrating participation, collaboration, real-world problem-solving, and interdisciplinary learning.

The European Competence Framework for Sustainability (GreenComp) defines competencies for tackling global challenges, such as climate change, biodiversity loss, and social inequity [9]. It emphasises systems thinking, critical reflection, and collective problem-solving, aligning with the Sustainable Development Goals [5].

To effectively foster these competencies in situated, real-world contexts, the integration of mobile technologies offers promising pedagogical affordances. Mobile devices, as ubiquitous tools, can support action-oriented pedagogy by enabling seamless transitions between learning contexts [10]. In a recent study, Mercan and Selçuk [11] show that location-based biology games enhance learners' awareness of environmental issues by linking abstract concepts to tangible real-world contexts. Similarly, Tan and Nurul-Asna [12], in a systematic review, identify critical success factors for serious games in environmental education, such as immersion, alignment with real-world challenges, and educational coherence.

Augmented reality (AR)-enhanced environments bridge theory and practice, linking knowledge with real-world challenges [13] and positively influencing attitudes towards sustainability [14]. Games, when combined with AR, provide an immersive interface [15] that integrates digital information into physical spaces, supporting situated learning [14,16]. This aligns with smart city concepts, enhancing urban sustainability through technology.

Mobile augmented reality games (MARGs), both in and out of school, promote peer scaffolding and collaborative discourse, which are crucial for social learning [17]. MARGs are increasingly recognised as valuable tools for promoting sustainability learning. Integrating MARGs into sustainability education fosters experiential, interactive learning [18,19], contextualising sustainability concepts while developing competencies like anticipatory thinking and strategic action [13,20]. Mobile devices facilitate game-based learning, an approach that has been shown to be effective in sustainability education [7,21,22].

1.1. Gaming for Sustainability Education

In a study by Strada et al. [23], a serious game about sustainability was developed based on AR, with the aim of contextualising the meanings related to sustainability in the learning environment. The findings of this study indicated that this approach led to a substantial enhancement in users' awareness of and commitment to sustainability. The self-reported questionnaires completed by users demonstrated the value of integrating AR technologies into learning about the Sustainable Development Goals. The integration process was found to have a positive impact on users' commitment and motivation levels, thereby enhancing their commitment to objectives that are aligned with the principles of ESD.

'Tipping Point' [19] is another example of a board game designed to simulate the complexity and interdependence of environmental, social, and economic systems. This game was analysed in a study that explored the effects of iteration on gameplay strategy. A total of 70 participants from three academic programmes were involved in the study, and the results indicated that initially, players pursued short-term, individualistic strategies; however, as the game progressed, they progressively adopted more collaborative

and long-term approaches. This transition was facilitated by mechanisms such as random resource allocation, spatial constraints, and structured debriefing sessions. The game design intentionally incorporates features of complex systems, including emergence, feedback loops, and uncertainty, thus rendering it a potent experiential learning instrument. The findings indicate that repeated exposure to simulated sustainability dilemmas can engender key competencies such as anticipatory thinking, collaborative problem-solving, and strategic planning. The authors place significant emphasis on the importance of aligning game mechanics with educational objectives. Furthermore, the manner in which gameplay failures functioned as leverage points for reflection and behavioural adaptation is also highlighted.

1.2. The EduCITY Approach for EDS

Building on the literature findings, the EduCITY project (https://educity.web.ua.pt/, accessed on 4 June 2025) exemplifies a next-generation approach by embedding the principles of sustainability education into a digitally enhanced, location-based learning environment in formal and informal educational settings.

Taking a different approach from 'Tipping Point', EduCITY promotes sustainable cities through a smart learning environment that integrates a mobile application featuring AR, environmental sensor data, 3D animations, and interactive educational content, all contextualized along real urban paths. This integration offers a context-based learning experience that not only aligns with formal educational goals but also encourages active engagement with real-world sustainability challenges. EduCITY leverages the motivational affordances of AR and game-based learning while fostering key competencies for sustainability. The associated web platform enables citizens to create games without requiring programming skills, following a socio-constructivist approach [24]. This pedagogy harnesses mobile technology to facilitate hands-on learning, enhancing environmental awareness and transforming cities into living laboratories within a citizen science framework.

With a focus on developing sustainability competencies, the project encourages interdisciplinary, real-world learning, extending learning opportunities beyond the classroom [25]. EduCITY raises awareness of urban heritage and sustainable development, positioning itself as a benchmark in ESD. By treating urban spaces as experimental laboratories, it fosters participatory learning aligned with the Open School movement [25,26] The model is replicable across cities, challenging traditional education approaches [26] and encouraging sustainable urban habits.

EduCITY and 'Tipping Point' [19] are aligned, particularly in their use of active, interdisciplinary, and immersive methodologies to foster environmental awareness and critical sustainability competencies. However, 'Tipping Point' is not digitally integrated nor designed to align with formal curricula or situated, real-world contexts. EduCITY, by contrast, addresses these dimensions through mobile augmented reality microgames embedded in local heritage settings and explicitly mapped to sustainability competencies as defined in the GreenComp framework [9]. This highlights the potential of digitally enhanced, location-based learning to bridge the gap between abstract competency models and [9] concrete, engaging learning experiences. In this context, MARGs offer an opportunity to situate sustainability education in real-world contexts. This study addresses an important gap in the literature by exploring how such games can foster key competences and how these can be meaningfully assessed. Hence, EduCITY's and this paper's research question is the following: How does a smart learning city environment—integrating a mobile app with co-created AR-enhanced games—promote changes in citizens' knowledge, skills, values, and attitudes for sustainability? [25]. In a mixed-method approach, the study evaluates MARG impact on sustainability education by triangulating participants'

perceptions of the project's activities' effectiveness, collected in a self-administered GreenComp-based questionnaire (GCQuest), with automated game performance logs. To ensure the validity of the quantitative data drawn from 358 questionnaires, a Structural Equation Model (SEM) was developed, confirming the internal coherence and factorial validity of the responses.

This paper continues with a description of the materials and methods, structured into three subsections: 'Activities and Participants', 'Data Collection', and 'Data Analysis'. It then presents the main results and discussion, addressing participants' perceptions of this project's contribution to education for sustainability, triangulated with the game logs. The paper concludes with the key findings, a discussion of the study's limitations and suggestions for future research directions.

2. Materials and Methods

Mixed-method research approaches [27] are known for combining qualitative and quantitative elements, within a robust and balanced methodological design to achieve a level of understanding and corroboration that would not be possible through either approach on its own.

Accordingly, a mixed-methods approach is employed to evaluate the value of the activities in promoting the 'Embodying Sustainability Values' area of the GreenComp competency framework [9]. Thus, this option positions this study within the broader context of European policy priorities for sustainability education.

This section presents, firstly, the EduCITY activities and participants; secondly, the data collection process; and thirdly, the data analysis method.

2.1. EduCITY Activities and Participants

Data collection was conducted through gameplaying activities with students across different academic levels, and teachers. These activities took place over one year, from February 2024 to February 2025, in different locations throughout the Aveiro urban area.

In each activity, the project is presented to the students, as well as the game's objectives and instructions on how to use the EduCITY app. Subsequently, the students are divided into groups, with 3 to 4 members, using the project's mobile phones, one per group. While these activities are conducted in a structured setting with students, the games are open to the public and freely available for anyone to play or test.

The gameplaying activities analysed in this work are directed to participants from 10 years-old to adults, from the 2nd Cycle of Basic Education (CBE) to higher education educational contexts. The present study focuses on the games developed by the project's team, excluding those developed by teachers in continuous training, undergraduate students, and master's students. Thus, the considered games are *Visit to the Salt Pans*, *EduCITY at the University Campus*, *Aveiro, cidade de Arte Nova e Liberdade* [*Aveiro, City of Art Nouveau and Liberty*], *Art Nouveau Path: From Heritage to Sustainability*, and *Aveiro Walking Tour*. A brief explanation of these games is provided in Appendix A. At the end of each activity, games scores are collected; thus, the three highest-scoring groups are awarded small prizes, and the remaining receive a participation gift, enhancing motivation.

Table 1 presents the number of activities (15 in total) and participants (374 in total), per school level, suggesting a substantial engagement and diversity across the involved school levels. This reveals an effort to tailor educational interventions to different age groups, ensuring relevance and effectiveness, in accordance with the literature recommendations [28]. No demographic data on the participants were collected in compliance with personal data protection regulations.

Table 1. Synthesis of the games, number of activities, and number of students who played each game, by academic level.

Name of the Games	Number of Activities	Number of Players				
		2nd/3rd CBE	Secondary Education	Higher Education	Teacher Training	Total
Visit to the Salt Pans	1	30	-	-	-	30
EduCITY at the University Campus	2	-	27	46	19	92
Aveiro, City of Art Nouveau and Liberty	1	20	-	-	-	20
Art Nouveau Path	9	118	49	25	-	192
Aveiro Walking Tour	1	-	-	-	40	40
Total	**15**	**168**	**76**	**71**	**59**	**374**

2.2. Data Collection

The data collection process comprised (a) the administration of a questionnaire, and (b) the gathering of automatic and anonymous game logs.

At the end of the gameplaying activity, each participant was invited to complete the anonymous questionnaire GCQuest, available in English (https://doi.org/10.5281/ZENODO.14524933) and in Portuguese (https://doi.org/10.5281/ZENODO.14197625), developed by the team, as described in Ferreira-Santos and colleagues [29].

The GCQuest was developed with the objective of providing a valuable contribution to addressing the formulated research question, particularly regarding the assessment of the 'Embodying Sustainability Values' area of the GreenComp framework [9]. The questionnaire was designed to offer sufficient scope for application in research or studies emerging from the EduCITY approach, or even for broader use in other research contexts, as explained by Ferreira-Santos et al. [29]. The questionnaire aims to evaluate participants' perceptions about the EduCITY activities on education for sustainability.

The GCQuest comprises two open-ended questions and one Likert scale question with 25 statements, where 1 corresponds to 'disagree' and 6 to 'agree'. The open-ended questions complement the quantitative data, as the first question was designed to identify the key learning outcomes of the game, and the second one to evaluate the participants' understanding of the sustainability concept. The Likert scale question was designed to analyse and evaluate three dimensions, corresponding to the following GreenComp competencies: 'Valuing Sustainability', 'Supporting Fairness', and 'Promoting Nature'. Each dimension is further structured in Knowledge, Skills, and Attitudes (KSAs). This questionnaire was applied across all educational levels.

The app includes automated mechanisms for generating game logs. These game logs record three variables: AR score; final score; and number of questions answered correctly and incorrectly. The 'AR Score' refers to the score obtained specifically through the Augmented Reality (AR) component of the game. This score is calculated based on the number of correct answers given during the AR-based tasks. Each correct answer awards the player a fixed number of points, and no points are given for incorrect answers. The 'Final Score' corresponds to the total score obtained in the game, which includes points from both the AR component and any additional questions. Data were collected by the app and anonymously uploaded to the EduCITY web platform, ensuring user privacy while still enabling data analysis. This provides measurable indicators of user engagement and information interpretation, enabling the evaluation of the EduCITY games effectiveness in achieving their educational goals. By leveraging this gameplay data, it is possible to identify trends, such as performance variance in longitudinal studies or difficult questions that can inform game improvements. All participants in the same game session received the same number of questions, and the content of the questions is identical for all users

involved in a given version of the game. This consistency ensures fairness in the gameplay experience and allows for comparability of results across participants.

This data collection process received approval from the institutional General Data Protection Regulation (GDPR) board. Thus, all data collection, processing, and storage procedures were conducted in accordance with the principles of research ethics. For example, participants completed the questionnaire voluntarily, after playing the selected game. Chen [18] employed a comparable methodology, which reveals effectiveness in sustaining student motivation and enhancing data quality, as evidenced by a lower incidence of incomplete or invalid questionnaire responses.

2.3. Data Analysis

Data were analysed using thematic analysis [30] for qualitative data (responses to open-ended questions), and both descriptive and inferential statistics [31,32] for quantitative data (answers to the Likert-scale items), as described below.

Although 374 participants engaged in the activities, not all opted to complete the voluntary questionnaire. A total of 368 responses were collected. Of these, 11 questionnaires were excluded from the analysis due to incomplete or invalid responses, yielding 358 validated questionnaires. This corresponds to a validated response rate of approximately 95.70%, which is considered high for voluntary survey-based research [33].

As the open-ended questions were designed to explore the content students perceived they had learned through the activities, a qualitative thematic analysis was undertaken following the reflexive approach proposed by Braun and Clarke [30]. The unit of analysis was the main themes identified in the answers. The coding process integrated inductive and deductive logic. The deductive approach was informed by the GreenComp framework [9], which offers a validated definition of sustainability. Hence, the authors collaboratively defined an initial scheme of analysis sustained in this framework. This alignment reflected the authors' expectation that the activities would foster learning within the domain of sustainability. However, given the broader scope of potential learning outcomes, an inductive approach was also employed. In the coding process, one author carried out the preliminary coding of all responses, crossing the initial scheme of themes with a close interpretation of data, with some themes and subthemes being generated or adjusted from participants' responses. Subsequently, the entire research team reviewed the coded data. Points of divergence were identified and discussed collectively, ensuring that multiple perspectives were considered. This process enabled the authors to refine the interpretations and enhance the validity of the analysis through consensus coding, a well-established method for improving reliability in team-based qualitative research [34]. No sampling was performed; therefore, all validated responses were included to ensure a comprehensive and inclusive analysis. At the end of the process, all units of analysis were organised into mutually exclusive subthemes.

The Likert-scale question was submitted to descriptive statistics of frequencies [31] and analysed with the GCQuest analysis tool [35]. After inputting data, the tool presents a color-coded graph with all the questionnaire statements, offering a global perspective on the dataset and supporting the identification of patterns in respondents' answers. Analysis includes the possibility of applying filters on specific competencies ('Valuing Sustainability', 'Supporting Fairness', and/or 'Promoting Nature') and domains (KSAs).

To validate the factorial structure of the questionnaire constructs, a second-order confirmatory factor analysis was conducted within a Structural Equation Model (SEM) [32,36] in JASP 0.19.3 (see the detailed analysis in https://zenodo.org/records/15768134). The model consisted of three first-order latent variables, the KSA dimensions (Knowledge, Skills, and Attitudes), each measured using multiple items rated on a 6-point Likert scale, without a neutral midpoint [36]. This forced-choice format encouraged participants to

express either agreement or disagreement, avoiding midpoint responses and thereby potentially enhancing measurement sensitivity.

The KSA constructs were specified to load onto a second-order factor representing 'Embodying Sustainability Values', reflecting a hierarchical conceptualization. Given the ordinal nature of the response scale, the Diagonally Weighted Least Squares (DWLS) estimator was used, which is appropriate for Likert-type data and accounts for non-normal distributions. This analysis can be conducted using JASP 0.19.3 for handling Likert-type data robustly.

The model demonstrated good fit using established indices: Comparative Fit Index, CFI = 0.945; Tucker-Lewis Index, TLI = 0.939; Standardized Root Mean Square Residual, SRMR = 0.049. The Root Mean Square Error of Approximation reflected acceptable error of approximation (RMSEA = 0.077). Also, all factor loadings were statistically significant ($p < 0.001$). These findings reinforce the internal coherence of the instrument and support its validity in alignment with the GreenComp framework [9].

The game logs were submitted to descriptive statistics regarding average, standard deviation, and range of the game final scores, game AR scores, and correct and incorrect answers. Playtime was excluded from the analysis due to its irrelevance to the study's primary research objectives. Furthermore, game duration is not necessarily indicative of performance, since participants may complete the activity quickly without correctly answering questions or fully engaging with the educational resources available, such as AR content, 3D models, images, or supplementary information. Consequently, playtime data were not included in the scope of this study.

Finally, the questionnaire and app log data were triangulated to provide a more comprehensive understanding of the activities' ability to promote changes in knowledge, skills, values, and attitudes in citizens to empower them towards sustainability. The results and discussion of the analysis are presented in the following section.

3. Results and Discussion

This section reports the study main results and their discussion considering the consulted literature.

3.1. Participants' Perception About the Activities' Contribution to Education for Sustainability

The results presented in this section are based on data collected with GCQuest [29] from 358 respondents. The initial question of the questionnaire required participants to identify two or three insights learned with the game, as detailed in Table 2. A total of 511 units of analysis were analysed.

Four overarching themes emerged from the analysis: 'cultural awareness', 'environmental protection', 'sustainability awareness', and 'contextual knowledge'. Each theme comprises specific subthemes grounded not only in GreenComp [9], but also in an inductive process based on participants' responses and in the educational aims of the activities.

'Cultural awareness' was the most prominent theme, encompassing 59.49% of the coded units, overwhelmingly dominating participant responses. Within this theme, 'local culture' is the only subtheme identified. This outcome resonates with Baumber's [37] emphasis on integrating learners' lived experiences and socio-cultural contexts into sustainability education. Baumber conceptualizes such contexts as 'real-world labs', capable of fostering transformative learning by anchoring content in local realities.

'Environmental protection' included 15.46% of responses, distributed across five subthemes: 'waste management' (5.68%), 'natural resources management' (3.91%), 'biodiversity preservation' (3.33%), 'environment/nature' references (1.76%), and mentions of 'local natural resources' such as salt (0.78%). These subthemes reflect varying degrees of participant engagement with environmental sustainability competencies.

In contrast, 'sustainability awareness' accounted for the fewest references (3.52%), with participants primarily identifying elements of 'concept knowledge information' (2.15%) and 'sustainability values' (1.37%). Although this low frequency may suggest a limited perceived impact of the game on values-related learning, it could also imply that participants already felt aligned with sustainability values. This interpretation is supported by Alkaher et al. [38], who argue that cultural backgrounds can shape learners' self-perceptions regarding sustainability, often embedding these values implicitly through daily practices and societal norms.

Lastly, the 'contextual knowledge' theme included a single subtheme, 'specific knowledge information', with 21% of the units coded. These responses suggest that gameplay activities may foster context-specific or disciplinary knowledge. As Oliveira et al. [39] point out, gamification strategies can yield broader educational benefits, promoting diverse cognitive and behavioural outcomes that extend beyond initial learning goals.

Table 2. Synthesis of the participants' responses about what they learned from the activities.

Theme	Subtheme	Descriptor	Citation (Translated Sentence)	N	Rel. Freq (%)
Cultural Awareness	Local culture	Engagement with local identity, traditions, and heritage	'[Learn about the Arte Nova Museum and the José Estêvão Monument]'	304	59.49
Environmental Protection	Waste management (e.g., microplastics, food waste)	Consequence awareness and actions related to reducing, reusing, and recycling waste	'[Food waste at the University]'	29	5.68
	Natural resources management (e.g., water, soil, stone and wood as building materials)	Responsible use and understanding of ecological materials	'[Examples of Art Nouveau buildings; **sand/adobe constructions**; **materials used**]'	20	3.91
	Biodiversity preservation	Appreciation and care for ecosystems and species diversity	'[**Preserving the environment and animals**; What is salt and salt pans; Microplastics]'	17	3.33
	Environment/ nature	General concern and connection to the natural world	'[**soil composition**, statue materials, carder materials]'	9	1.76
	Local natural resources (e.g., salt)	Knowledge of region-specific environmental assets	'[**Curiosities about salt** and microplastics]'	4	0.78

Note: As participants were allowed to submit up to three responses, the bolded entries in the table correspond to the subthemes under which each unit of analysis was categorized.

This analysis revealed meaningful learning across four thematic areas: cultural awareness, environmental protection, sustainability awareness, and contextual knowledge. The predominance of local cultural insights highlights the power of place-based, context-rich experiences in sustainability education. Although references to values were less frequent, the findings suggest that participants may already embody sustainability principles shaped by their cultural context. Moreover, the acknowledgement of learning knowledge not explicitly related to sustainability points to the broader educational potential of gamified learning environments like EduCITY.

The second question required participants to express their own understanding of sustainability, as detailed in Table 3. A total of 392 units of analysis were identified in the responses to this question, in the three themes selected from the GreenComp [9]: 'values and behaviours', 'present actions', and 'future thinking'. The most frequently cited

subtheme, 'responsible use of resources' (23.79%), reflects an awareness of humanity's integral role within Nature and the necessity of conserving resources. This emphasis is consistent with GreenComp's competence of 'Promoting Nature', which underscores the importance of recognizing humans as part of Nature and respecting the rights of other species to restore resilient ecosystems.

Similarly, 'environmental preservation' (23.27%), on the theme of 'present actions', emerged as a key concern, with participants highlighting personal responsibility and proactive measures towards a healthier planet. This finding aligns with the 'Individual Initiative' competence in GreenComp, which encourages individuals to actively contribute to sustainability efforts.

The theme of 'future thinking' was also prominent, with its single subtheme of 'intergenerational equity' (21.74%). This resonates with GreenComp's 'Futures Literacy' competence, which involves imagining and developing alternative sustainable future scenarios.

In contrast, fewer responses referenced 'sustainable lifestyle' (6.14%) or 'sustainable values' (2.30%), suggesting that more abstract or reflective aspects of sustainability may be less commonly articulated among participants. This observation is notable, as it may indicate a gap in the integration of sustainability values into personal and collective worldviews, an area identified as crucial in sustainability education.

Additionally, a significant proportion of the responses (22.76%) did not provide an explicit definition of sustainability, indicating either ambiguity in understanding of the concept or divergence from the conceptual framework adopted by this paper authors. This underscores the ongoing challenge in sustainability education to foster a comprehensive and universally understood set of competences.

Table 3. Synthesis of the participants' responses about their own understanding of sustainability.

Theme	Subtheme	Descriptor (Based on GreenComp Framework)	Citation (Translated Sentence)	N	Rel. Freq (%)
Values and behaviors	Responsible use of resources	To acknowledge that humans are part of Nature; and to respect the needs and rights of other species and of Nature itself to restore and regenerate healthy and resilient ecosystems	'[Don't spend all resources in the present']	93	23.79
	Sustainable lifestyle	To support equity and justice for current and future generations and learn from previous generations for sustainability	'[Sustainability is essential if we are to continue living on our planet.']	24	6.14
	Sustainable values	To reflect on personal values; identify and explain how values vary among people and over time, while critically evaluating how they align with sustainability values	'[the formation of aware and committed citizens for a balanced future']	9	2.30
Present actions	Environmental preservation	To identify own potential for sustainability and to actively contribute to improving prospects for the community and the planet	'[It's about being responsible towards nature and the animals around us. In this way we can have a more cared and healthier planet to live on.']	91	23.27
Future thinking	Intergenerational equity	To envision alternative sustainable futures by imagining and	'[thinking about the future of the planet']	85	21.74

developing alternative scenarios and identifying the steps needed to achieve a preferred sustainable future | To manage transitions and challenges in complex sustainability situations and make decisions related to the future in the face of uncertainty, ambiguity and risk		
(Unspecified information or not related to sustainability)	89	22.76

The third question of the questionnaire comprised 25 statements, subdivided into three GreenComp competences: (a) 'Valuing Sustainability'; (b) 'Supporting Fairness'; and (c) 'Promoting Nature'. Graphs were created with the GCQuest analysis tool [35], as illustrated in Figure 1. As a paired Likert scale was used, it does not include a neutral midpoint. Consequently, the responses provided can be classified as either positive or negative, with values between 1 and 3 being interpreted as negative perception (red to yellow colours) and those between 4 and 6 as positive (light to dark green).

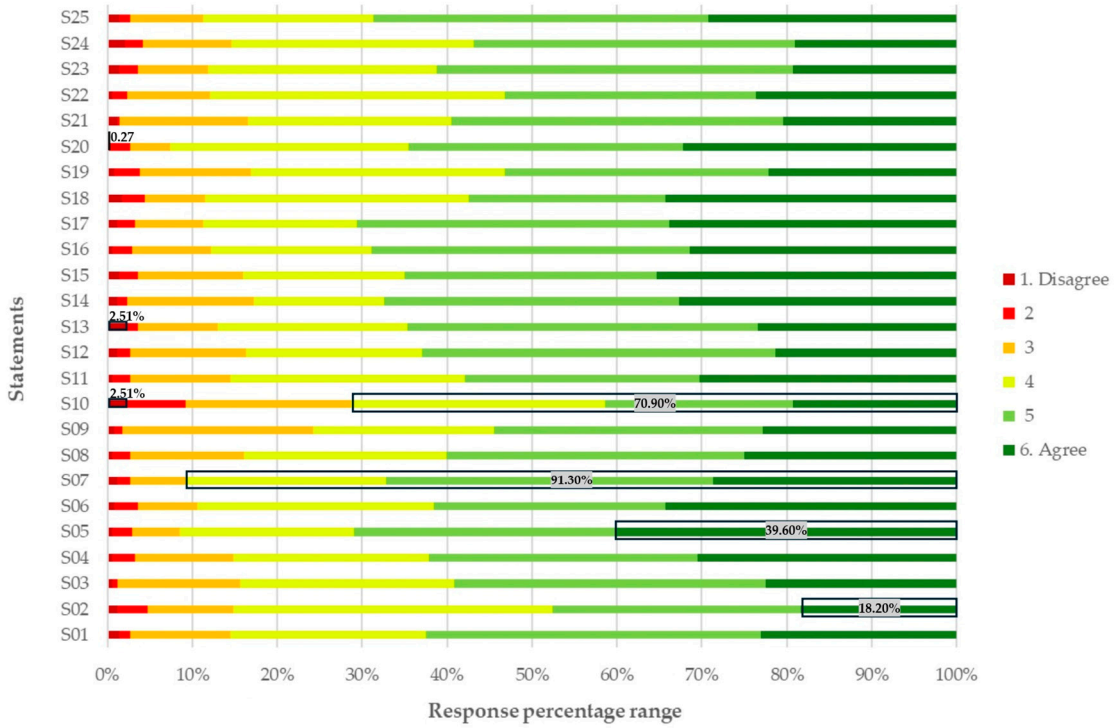

Figure 1. Respondents' perception on the competence dimensions and typologies of the 'Embodying Sustainability Values' competence area.

Statements: S01 "… be prone to act in line with values and principles for sustainability.", S02 "… articulate and negotiate sustainability values, principles and objectives while recognising different viewpoints, while recognizing different points of view.", S03 "… identify processes or action that avoid or reduce the use of natural resources.", S04 "… know that damaging and exhausting natural resources can lead to disasters and conflicts (e.g., loss of biodiversity, draughts, mass migration and war).", S05 "… show empathy with all life forms.", S06 "… evaluate issues and action based on sustainability values and principles.", S07 "… be able to acknowledge cultural diversity within planetary limits.", S08 "… be able to apply equity and justice for current and future generations as criteria for environmental preservation and the use of natural resources.", S09

"… know about environmental justice, namely considering the interests and capabilities of other species and environmental ecosystems.", S10 "… know the main views on sustainability: anthropocentrism (human-centric), technocentrism (technological solutions to ecological problems) and ecocentrism (nature-centred), and how they influence assumptions and arguments.", S11 "… be committed to decreasing material consumption.", S12 "… be able to bring personal choices and action in line with sustainability values and principles.", S13 "… be willing to share and clarify views on sustainability values.", S14 "… be able to find opportunities to spend time in nature and helps to restore it.", S15 "… be able to see and imagine humans living together and respecting other life forms.", S16 "… know that values and principles influence action that can damage, does not harm, restores or regenerates the environment.", S18 "… care about a harmonious relationship existing between nature and humans.", S19 "… respect, understand, and appreciate various cultures in relation to sustainability, including minority cultures, local and indigenous (from a region) traditions and knowledge systems.", S20 "… be able to assess and question personal needs to carefully manage resources in the pursuit of longer-term goals and common interests.", S21 "… be able to assess own impact on nature and consider the protection of nature an essential task for every individual.", S22 "… know that individuals and communities differ in how and how much they can promote sustainability., S23 "… be able to help build consensus on sustainability in an inclusive manner.", S24 "… be able to identify and include values of communities, including minorities, in problem framing and decision making on sustainability.", S24 "… know that people are part of nature and that the divide between human and ecological systems is arbitrary.", S25 "… be ready to critique and value various cultural contexts depending on their impact on sustainability."

Graph 1 provides a global perspective on the collected data, revealing predominant trends and patterns. More specifically, respondents tended to agree with the questionnaire statements, as evidenced by the predominance of green colours in each statement, varying between 70.9% (from 358 respondents) for S10, which addresses the main views on sustainability and how they influence assumptions and arguments, and 91.3% for S07, which focuses on acknowledging cultural diversity within planetary limits. Moreover, all the statements gathered at least 18.2% of answers (S02) in the highest level of agreement (option 6 of the scale), with a maximum of 39.6% (S05). In contrast, at the other extreme of the scale, the highest disagreement category (stronger red colour) varied between 0.27% (S20, about the dilemma of fulfilling personal needs vs. resources management) and 2.51% (S10 and S13, which address the willingness to share and clarify sustainability values). In sum, the results presented in Figure 1 indicate that participants have an overall similar perception of the activity they experienced, and perceive that this activity supports the development of the competency area 'Embodying Sustainability Values'.

In the 'Dynamic Tables and Graphs' worksheet of the GCQuest analysis tool, applying the filter to the KSA typologies produces the next set of graphs. Figure 2 presents the analysis of the 'Knowledge' typology, Figure 3 presents analysis of the 'Skills' typology, and Figure 4 presents the analysis of the 'Attitudes' typology.

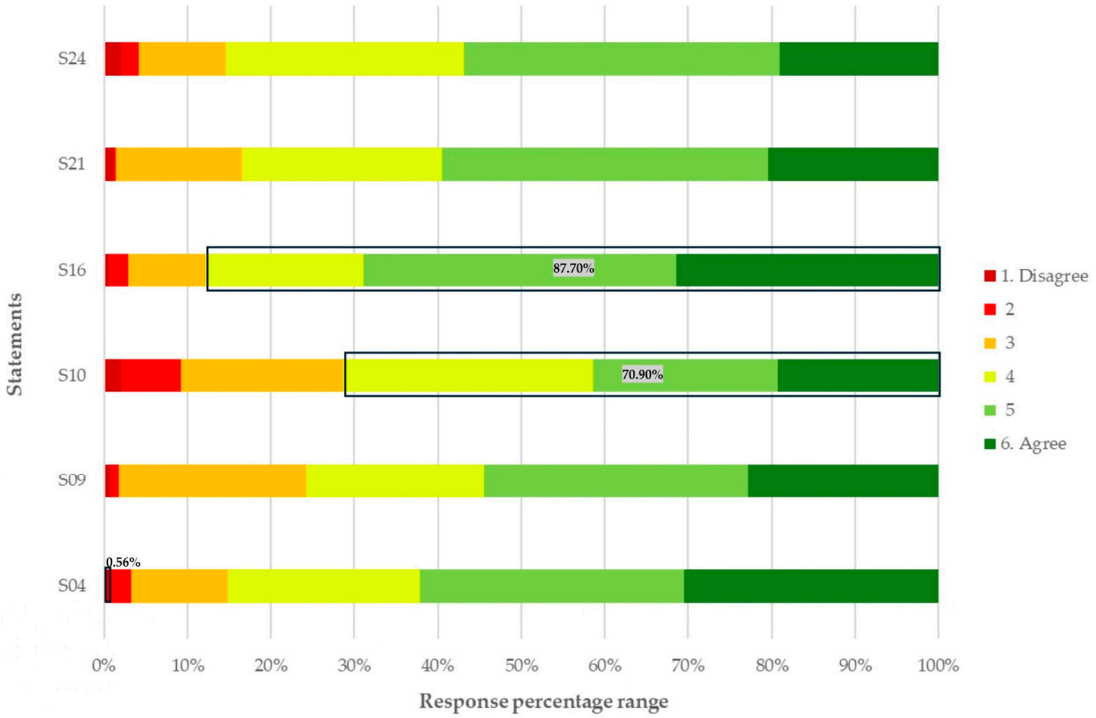

Figure 2. Respondents' perception on the Knowledge Ttypology of the 'Embodying Sustainability Values' competence area.

Figure 2 offers a detailed perspective on participants' knowledge-related responses, showcasing general patterns of agreement across selected statements. A clear tendency toward agreement is visible, with green tones (categories 5 and 6) prevailing in each of the statements shown. Notably, statement S16, which refers to values and principles regarding the environment, stands out with 87.70% agreement, highlighting a strong consensus on this conceptual aspect of sustainability.

Statement S10, on the other hand, presents the lowest rate of agreement within this graph (70.9%), relating to the understanding of how sustainability views influence assumptions and arguments. This statement also gathers a higher proportion of responses in the disagreement categories, indicating a slightly more varied level of knowledge or confidence in this item. This observation is in line with previous findings in Figure 1, where S10 also demonstrated a comparatively lower agreement rate.

Another notable case is S04, with only 0.56% of participants selecting the extreme end of disagreement, considering that the activity contributes to knowledge about the consequences of damaging and exhausting natural resources, thus further reinforcing the overall tendency towards agreement across all items.

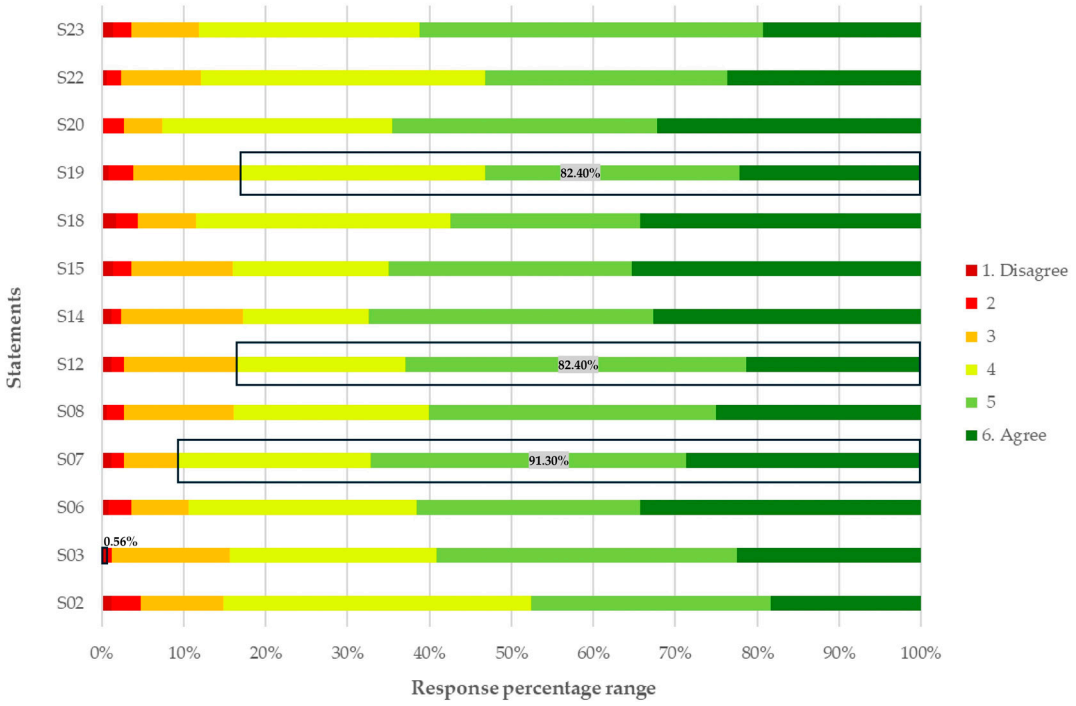

Figure 3. Respondents' perception on the Skills typology of the 'Embodying Sustainability Values' competence area.

Figure 3 illustrates the distribution of responses regarding the skills-related statements, also highlighting consistent agreement across all items. Again, the dominance of green tones across all statements suggests a strong alignment with the skill-based dimensions of the activities. Particularly, statement S07—focused on acknowledging cultural diversity within planetary boundaries—stands out with 91.30% of responses falling into the highest agreement categories, demonstrating the participants' perception regarding a strong commitment to inclusive sustainability values concerning cultural diversity.

Statement S12, related to personal choices and action in line with sustainability values and principles, and S19, related to respecting, understanding, and valuing diverse cultures, achieved the lowest levels of agreement, but still revealed hight positive agreement perceptions (82.40% each).

As in previous graphs, disagreement remains marginal, with, for example, S03 showing only 0.56% of responses in darker red, the highest disagreement category.

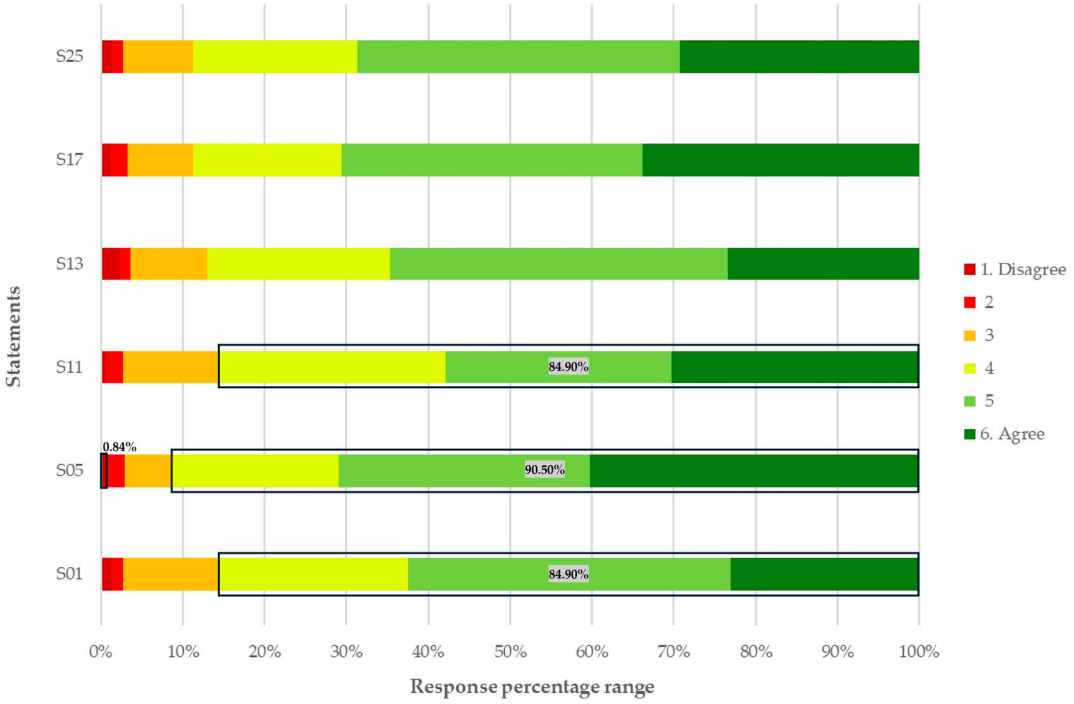

Figure 4. Respondents' perception on the Attitudes typology of the 'Embodying Sustainability Values' competence area.

Figure 4 provides a focused view on the distribution of attitudes towards specific statements, highlighting key patterns among participant responses. Overall, similar to the previous analysis, there is a strong tendency towards agreement. Notably, statement S05, regarding empathy with all life forms, stands out with 90.5% of agreement (5th or 6th scale options).

In contrast, statements S01 and S11 present the lowest range of positive level of agreement, yet still reached a high score (84.90% of agreement). This echoes the overall trend in the dataset, where disagreement remains consistently low across statements, and is particularly minimal in items related to participants' personal sustainability values and ethical reasoning.

In summary, the response patterns across Figures 2–4 indicate that the activities effectively promote sustainability-related knowledge, skills, and attitudes, in coherence with Figure 1. Additionally, the activities foster practical, collaborative, and reflective skills, reinforcing the GreenComp area 'Embodying Sustainability Values'.

3.2. Game Logs: Educational Value

Table 4 displays the game log data of completed games that were successfully uploaded to the EduCITY web platform. These logs provide indicators of the games' educational value in relation to sustainability promotion. Each game log corresponds to the activity of a group of participants (typically comprising 3 to 4 members), who engaged collaboratively in gameplay. Between 5 and 59 logs were collected, providing data for subsequent analysis. The data pertaining to the final score, AR score, and the number of correct and incorrect answers are automatically generated by the mobile devices and uploaded to the project web platform upon game completion. The data were anonymous and accessed only by the project team.

Table 4. Average, standard deviation, minimum and maximum score for the final score, correct and incorrect answers of game logs collected in the EduCITY web platform.

		Games				
		Visit to the Salt Pans	***EduCITY on University Campus***	***Aveiro, City of Art Nouveau and Liberty***	***Art Nouveau Path: From Heritage to Sustainability***	***Aveiro Walking Tour***
Number of groups who played the game		7	39	5	59	14
Final score	Average	64.29%	76.70%	86.40%	83.30%	66.30%
	Standard deviation	5.34	10.33	5.35	29.77	19.83
	Minimum-maximum	50.00% - 71.40%	35.00% - 100.00%	75.30% - 90.90%	33.33% - 100.00%	29.20% - 95.00%
AR score	Average	56.25%	86.84%	81.81%	75.00%	81.80%
	Standard deviation	3.20	21.95	19.00	40.16	3.16
	Minimum-maximum	0.00% - 100.00	4.17% - 100.00%	83.33% - 100.00%	27.27% - 100.00%	57.14% - 100.00%
Correct answers	Average	64.30%	80.58%	85.40%	86.11%	72.40%
	Standard deviation	1.07	18.89	1.07	4.96	3.26
	Minimum-maximum	50,00% - 71.40%	45.83% - 100.00%	77.30% - 90.90%	44.44% - 100.00%	41.20% - 95.90%
Incorrect answers	Average	35.70%	19.42%	13.60%	13.89%	30.30%
	Standard deviation	1.07	5.11	1.07	4.96	3.55
	Minimum-maximum	28.60% - 50.00%	0.00% - 54.17%	9.10% - 22.70%	0.00% - 55.56%	4.20% - 62.50%

Table 4 organises the app game logs according to the game played. Since each game included a different number of questions and corresponding maximum scores, the results are presented as percentages, to ensure comparability across games. Therefore, final scores represent the proportion of correct answers relative to the maximum possible score for each game. Higher percentages indicate stronger educational achievement. To perform successfully, teams were required to observe their surroundings, consult the educational resources embedded in the app, critically evaluate alternative solutions to the challenges posed, and collaboratively negotiate their responses.

Participants achieved the highest average performance in the game *Aveiro, City of Art Nouveau and Liberty*, with a mean score of 86.40%, ranging from 75.30% to 90.90%, and a notably low standard deviation (SD = 5.35). This suggests a high degree of consistency in learning outcomes across participant groups, indicating that the game may have been particularly effective in supporting educational engagement and comprehension. The strong performance may be attributed to the clear pedagogical alignment between game tasks and intended learning outcomes, the intuitive structure of the game, and the relevance of the content.

Similarly, the game *Art Nouveau Path: From Heritage to Sustainability* yielded a high average score of 83.30%, though with the widest range in group performance (33.33% to 100.00%) and the highest standard deviation (SD = 29.77). This variation suggests differentiated levels of achievement, likely reflecting the heterogeneity of the participant profile. As shown in Table 1, participants in this game ranged from 3rd CBE to higher

education, thus encompassing a broad spectrum of prior knowledge, cognitive development, and collaborative experience. While some groups achieved higher performance, possibly due to older age or greater experience, others may have struggled to extract relevant information from the digital and physical components of the game.

Additionally, the EduCITY web platform recorded a markedly lower number of logs for *Aveiro, City of Art Nouveau and Liberty* (5 logs) compared to *Art Nouveau Path: From Heritage to Sustainability* (59 logs). This substantial discrepancy in log volume of game logs may have contributed to the observed consistency in the former, while the higher number and greater diversity in participant backgrounds in the latter may explain the wider variability in performance.

In contrast, the lowest average performance was observed in the game *Visit to the Salt Pans*, with a mean score of 64.29%, ranging from 50.00% to 71.40%, and a similarly low standard deviation (SD = 5.34). Although the narrow score range indicates consistent performance among groups, the overall lower scores suggest that this game may pose educational challenges. Several factors could account for this result. First, the cognitive demands of the tasks, the clarity of the instructions and the available resources may not have been adequately calibrated to the participants' prior knowledge or learning needs. This hypothesis aligns with literature indicating that task complexity and misalignment with prior knowledge can negatively affect learning outcomes [40]. Second, environmental and contextual factors during gameplay may have influenced participants' levels of engagement and overall performance. Notably, this game was implemented during a single event and under adverse weather conditions, specifically during rainfall. Such less favourable circumstances may have hindered participants' ability to concentrate, interact with their surroundings, and collaborate effectively. These findings align with research in mobile learning, which highlights the critical influence of physical context on learners' cognitive engagement and the quality of the learning experience [41].

For the AR Score, that is, the score achieved on questions associated with AR content (although with optional use), the highest performing game was 'EduCITY on University Campus'. This game reached an average AR score of 86.84%, with values ranging from 4.17% to 100.00% and a high standard deviation (SD = 21.95). This high variability, especially in contrast with the game average final score (76.70%), suggests differing levels of participant engagement with the AR features. The higher AR score relative to the final score (86.84% vs 76.70%) indicates that users who explored the AR content tended to perform better overall. Notably, this game underwent more refinement cycles by the team, which may explain both the improved AR outcomes and the wider performance variability, possibly reflecting increased interactivity, depth of content, or complexity introduced in the later versions.

Conversely, the lowest AR performance was recorded in *Visit to the Salt Pans*, with an average of 56.25% and a broad range from 0.00% to 100.00% and low standard deviation (SD= 3.20). This game included only one AR-enhanced question due to environmental constraints limiting the placement of durable AR markers in the salt pan context. The limited integration of AR elements likely contributed to the lower scores and diminished potential for engagement.

These findings highlight marked differences between final and AR-specific scores. While final scores tend to show more consistency across groups, AR scores exhibit greater dispersion, pointing to varying degrees of exploration and engagement with AR features. This suggests that while AR can enhance performance when explored, its impact is dependent on both the quality of integration and user uptake. Importantly, all games achieved positive average performances, aligning with questionnaire data that also pointed to the project's contribution to promoting sustainability learning through game-based experiences.

4. Conclusions

This study explored the pedagogical potential of MARGs within the EduCITY project, which aims to promote education for sustainability in urban environments. Drawing upon a mixed-methods design that combined self-reported data from a validated questionnaire (GCQuest) with automated game logs, the findings reveal that the activities are effective in fostering sustainability-related competencies, particularly in the area of 'Embodying Sustainability Values' as conceptualised by the GreenComp framework [9].

4.1. Key Findings and Educational Contributions

The results demonstrate that participants, spanning a wide range of educational levels, engaged meaningfully with the content and context of the games. The thematic analysis of open-ended questionnaire responses indicated learning outcomes across four principal domains: 'cultural awareness', 'environmental protection', 'sustainability awareness', and 'contextual knowledge'. The predominance of references to local heritage and environmental practices suggests that location-based AR games can effectively situate learning in meaningful real-world contexts, reinforcing the value of experiential and transformative pedagogies in sustainability education [8,37].

Moreover, the questionnaire results confirm that respondents perceived MARGs as potentially promoting not only cognitive understanding (e.g., knowledge of local culture and environmental protection) but also affective and behavioural dimensions, such as the alignment of values and intention to act, in coherence with GreenComp [9]. This reinforces the importance of adopting pedagogical models that move beyond knowledge transmission to include socio-emotional and ethical learning [4,5].

Participants' emphasis on local culture and contextually grounded environmental knowledge illustrates how learning becomes more meaningful when it is rooted in learners' lived realities. This supports the argument for place-based sustainability education [37], where physical environments act as 'living laboratories' for real-world problem-solving and civic engagement. Moreover, the educational content covered in the games, ranging from biodiversity to architecture and cultural identity, demonstrates the potential for cross-subject learning.

Game log analysis further supported these insights, providing quantitative indicators of performance and engagement. Notably, games with a stronger alignment between game tasks and intended learning outcomes, such as *Aveiro, City of Art Nouveau and Liberty*, achieved both high average scores and low performance variability, indicating robust learning outcomes. Conversely, games like *Visit to the Salt Pan*s with fewer AR questions and less favourable environmental conditions during gameplay, demonstrated lower performance levels, underscoring the importance of both content design and contextual variables in situated learning experiences [40,41].

Furthermore, the variability in AR-specific scores across games highlights both the opportunities and challenges of AR integration. While participants who engaged with AR content tended to achieve higher overall scores, suggesting the added pedagogical value of immersive digital media, not all learners decided to interact with these features. This variability points to the need for deeper consideration of user experience design, AR marker feasibility in natural outdoor settings, and instructional scaffolding to ensure effective engagement [13,16].

4.2. Advocating for Smart Learning City Environments in Sustainability Education

From the above considerations, ultimately, this study offers novel insights by empirically affirming the effectiveness of smart learning city environments, particularly the integration of co-created AR-enhanced mobile games for advancing sustainability education beyond traditional classroom boundaries. More specifically, and answering this

study research question, this smart learning city environment, integrating a mobile app with AR-enhanced games, seems to effectively promote changes in citizens' knowledge, skills, values, and attitudes towards sustainability. The findings are supported by convergent qualitative and quantitative evidence indicating that the activities foster a deeper understanding of sustainability concepts, particularly in areas such as environmental protection, cultural awareness, and responsible resource use, as detailed below.

Regarding knowledge (K), participants considered the activities to increase conceptual understanding in areas such as local culture, biodiversity, and environmental protection. High average scores in game logs may indicate cognitive gains. The open-ended responses highlighted contextual learning (e.g., materials used in construction, salt pans), reinforcing situated knowledge acquisition.

Evidence suggesting skills (S) development related to the considered competence area was primarily derived from participants' self-reported questionnaire responses, explicitly mapped to skill-oriented indicators grounded in the framework. By triangulating with quantitative evidence, support for skill development stems from the analysis of specific items within the S dimension (e.g., high agreement with statements S07, S12, and S19). However, it is important to emphasize that these are perceived skills, rather than direct performance measures.

Participants reported strong activity alignment with sustainability attitudes and values (A), such as empathy for life forms, equity, and justice. Although explicit references were less frequent in open-ended responses, high agreement levels on attitude-related items (e.g., S05, S17, and S25) suggest a coherent pattern of value-driven attitudes promoted by the game-playing activities.

In sum, this study makes an original and empirically grounded contribution to the field of MARGs by presenting indicators of their effectiveness to promote sustainability competencies, offering comparative insights into the influence of iterative game design and AR integration on learning outcomes. It demonstrates that participants engaging in MARGs within outdoor urban environments perceive that this activity does foster the GreenComp competence area 'Embodying Sustainability Values', encompassing KSAs, which are central to sustainability education. The study is distinctive in showing how context-aware, place-based digital games can serve as powerful pedagogical tools. These games provide interdisciplinary learning opportunities, bridging formal curricula with civic engagement and local heritage. Moreover, this study offers comparative insights into how game design (e.g., AR usage, game refinement) may influence learning outcomes, a less explored area in current education for sustainable education and MARG research. The educational value of this approach is supported by high levels of participant agreement with competence-related statements and consistent performance data from gameplay logs. By leveraging mobile technologies to connect learners with their environments, this study advances current knowledge on how immersive educational experiences can promote values-based sustainability competences.

4.3. Limitations of the Study and Future Research

Despite the promising results, several limitations should be acknowledged. The study design relied on single-session activities, limiting insights into the long-term impact of the EduCITY approach on knowledge retention or behaviour change. Additionally, participation in AR experiences was optional, resulting in varied engagement potentially influencing both performance and perception data. These limitations constrain the generalisability of the findings and highlight the need for future longitudinal and comparative studies that can assess the sustained effects of AR-enhanced game-based learning.

Another limitation relates to the absence of demographic data due to ethical and privacy considerations, which restricts more nuanced analysis of participant profiles and their relation to learning outcomes. Although demographic data (e.g., age or gender) was

not collected in this study to ensure anonymity, we acknowledge the relevance of such variables in future analyses and plan to incorporate them, ethically and anonymously, in subsequent studies to explore potential differences in engagement and competence development. Moreover, while the GCQuest demonstrated reliability and validity in capturing perceptions aligned with GreenComp competencies in a previous study [29], its applicability to younger learners (e.g., in primary education) remains limited. Future research will therefore focus on adapting the GCQuest to better serve primary education contexts. Improvements to the app's usability, accessibility, and visual appeal may enhance learner engagement across diverse user groups.

Another limitation concerns the fact that the questionnaire was administered only after the activity, making it difficult to entirely exclude the influence of participants' previous experiences on their reported perceptions of competence. However, the questionnaire items were explicitly framed in reference to the game-based activity, and participants' qualitative responses consistently referred to specific aspects of the gameplay. This suggests that their perceptions were largely shaped by the experience with the EduCITY app. Future studies should consider employing pre- and post-assessment designs to better isolate the impact of the intervention.

Moreover, the study did not include behavioral observation, performance-based task assessment, or longitudinal follow-up, which are widely considered more robust forms of evidence for actual skill development in educational research. Their absence limits the conclusions to perceived learning gains. Future research should therefore integrate direct and longitudinal assessment strategies to more accurately evaluate the acquisition and application of sustainability-related skills over time.

Although individual game scores were not correlated with questionnaire responses in this study due to anonymity and the collaborative nature of gameplay, future research could employ reflective and self-evaluative methods to better understand the relationship between team performance and perceived competence development.

Ultimately, this study affirms the value of integrating mobile technology and AR into game-based learning environments to cultivate sustainability competencies. It contributes to the growing body of literature advocating for context-rich, interactive, and learner-centred approaches to ESD, and highlights the role of smart learning city environments in shaping informed, reflective, and engaged citizens.

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Data Availability Statement: A printable version of the games is available at https://doi.org/10.5281/zenodo.15534671; the questionnaire data is available at https://doi.org/10.5281/zenodo.15324177 and the GCQUEST SEM EduCITY analysis is available at https://zenodo.org/records/15768134.

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Abbreviations

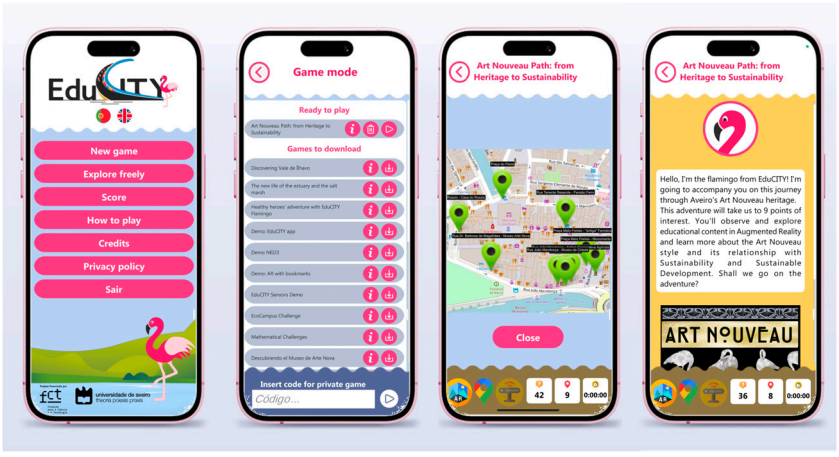
The following abbreviations are used in this manuscript:

MARGs	Mobile Augmented Reality Games
ESD	Education for Sustainable Development
AR	Augmented Reality
CBE	Cycle of Basic Education
KSAs	Knowledge, Skills, and Attitudes

Appendix A. Brief Description of EduCITY Games

The EduCITY app (freely available at https://educity.web.ua.pt/app.php, accessed on 04 July 2025) presents a set of games developed by the EduCITY team and by the educational community in which the players answer a series of interdisciplinary questions related to a given outdoor route. The (i) button in each game presents contextual information, such as level of education, subject(s), and number of points of interest and questions of the game.

Figure A1 illustrates a few screenshots of the EduCITY app. The welcoming menu (Figure A1A) serves as the initial user interface upon launching the application. This screen offers access to game instructions and navigation to available gameplay options, among other features. If the button "New game" is selected, the app shows the game listing interface (Figure A1B), which presents games into two main sections: games already available on the user device and games that can be downloaded. This organization supports user autonomy in selecting learning experiences aligned with their interests and context. During the game, users can access the in-game orientation map (Figure A1C), a key navigational tool that provides spatial awareness and contextualizes the player's position relative to various geo-referenced points of interest.



(**A**) (**B**) (**C**) (**D**)

Figure A1. EduCITY app and in-game screenshots: (**A**) Welcoming menu; (**B**) game listing (games ready to play and games available for download), (**C**) in-game orientation map with points of interest marked; (**D**) in-game initial message (example from *Art Nouveau Path: From Heritage to Sustainability*).

At the beginning of a selected game, the user is welcomed by the project's mascot, the Flamingo Mr. Pinky (Figure A1D), in the initial in-game message to present the main objectives of the game. This narrative element introduces the thematic scope of the activity and sets the tone for the learning journey. The structure of all games is consistent and divided into four categories: spatial orientation to find points of interest (Figure A2A), question introduction for contextualization (Figure A2B), question and answer options (Figure A2C), and feedback for either correct or incorrect responses (incorrect answer feedback illustrated in Figure A2D,E), presented by the app to the user.

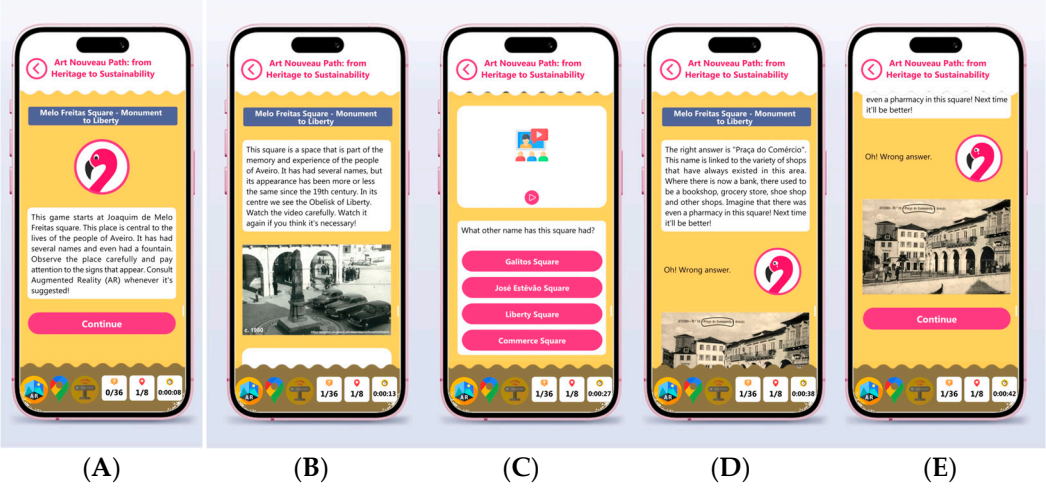


Figure A2. EduCITY app and in-game screenshots: (**A**) Spatial orientation to find one specific point of interest; (**B**) question introduction for contextualization, in this case with a supporting image; (**C**) the related question, in this case also with a supporting video, and answer options; (**D**) selected answer feedback, in this case related to incorrect answer; (**E**) supporting image to the feedback (example from *Art Nouveau Path: From Heritage to Sustainability*).

Furthermore, all games integrate multimedia resources (AR, videos and images). The game incorporates AR markers powered by Vuforia SDK, enabling users to interact with contextualized 3D models, videos, animations, and narrative elements embedded in the city environment, as shown in Figure A3.

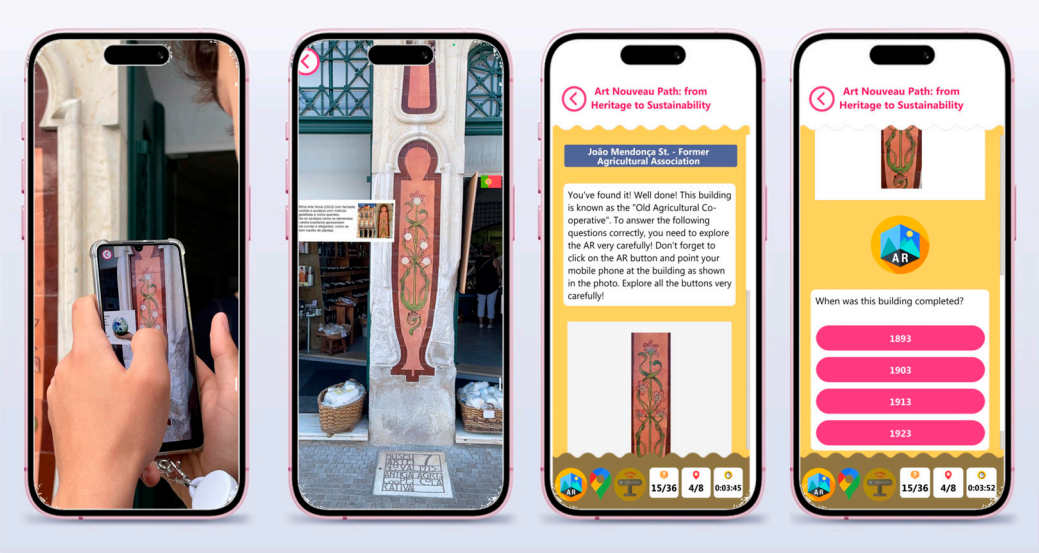


Figure A3. EduCITY app and two illustrative examples of in-game AR experience.

The central objective of these games is to promote education for sustainability. The link (https://doi.org/10.5281/zenodo.15534671) shows a PDF of the games analysed in this paper, including points of interest, an introduction to the questions, the questions themselves, feedback, resources in image format, and reference to selected videos and AR content.

Brief description of each game:

- *Visit to the Salt Pans*

This game was specifically designed for 3rd Cycle of Basic Education(CBE) students, most of whom are in the 8th grade, and for the general community. The game's objective is to promote ESD, with the aim of raising participants' awareness of the pervasive problem of micro-plastics. In addressing this issue, the game incorporates interdisciplinary content from the natural sciences, physical and chemical sciences, history, geography, and citizenship. Furthermore, students have the opportunity to develop a more profound comprehension of the functionality of salt pans and the salt production process. The game begins at Zé Penincheiro's tile panel entitled 'Voar mais alto' and swiftly arrives at its primary point, the 'Santiago da Fonte' salt pan, where the students walk for approximately 10 min. Following their entry, the students proceed to the warehouse, the salt pile, and the bird observatory, culminating their journey outside the salt pan at a palm tree located near the Aveiro lagoon [Ria de Aveiro]. The game incorporates fourteen multiple-choice questions accompanied by images, audio, video, and AR content. These AR elements provide additional information that enriches the real-world observations at one point of interest. To promote awareness of Aveiro's natural and cultural heritage, particularly its salt production and salt pans, a new AR marker has been developed for this game. In addition to the marker, new images and videos were created to facilitate learning.

- *EduCITY at University Campus*

This game is to be held on the University Campus Boulevard [Alameda], and it is intended for students in the 3rd CBE and secondary education. As they follow a predetermined path around the campus, students engage in a game that raises their awareness of the need for changes in attitudes towards nature conservation. Furthermore, the game fosters connections between the university's natural environment and curriculum-related content from Natural Sciences, History, and Citizenship. The game integrates 24 multiple-choice questions with images, audio, video, and AR content. These multimedia resources

complement the observable reality in each location. In this game, AR was integrated into the questions with two main aims: (i) to promote knowledge related to natural heritage (Botany), where AR markers are identification plaques for trees on the campus, in this case, the maidenhair tree and the Mediterranean cypress tree, and (ii) to promote knowledge related to aspects of the University Campus, which is the case of AR markers that are art tiles of the University.

- *Aveiro, City of Art Nouveau and Liberty*

The game was developed for students in the 3rd CBE. It aims to promote ESD through an exploration of Aveiro's cultural, historical, and artistic heritage. The game places emphasis on fundamental values such as liberty, democracy, and cultural identity by encouraging participants to engage with iconic landmarks and artistic elements of the city. The game starts at the tile panel entitled 'Voar mais alto'. Thereafter, students proceed along a path encompassing eight points of interest, including such iconic sites as the old hospital, Infante D. Pedro Park bandstand, the Fountain of the Five Spouts [Fonte das Cinco Bicas], Family and Children's Court–Aveiro District, Santa Joana Aveiro Museum, Carolina laurelcherry tree, and José Estêvão statue. Along the path, learners explore Art Nouveau architectural details, elements of urban regeneration, and local stories tied to liberty and civic engagement. The game comprises 22 multiple-choice questions, accompanied by images, audio, video, and AR content. Through the use of AR, students can access virtual information that serves to enhance their real-world observation. To illustrate this point, one may consider the viewing of digital overlays of the cherry laurel leaf, the olive tree, or the discovery of symbolic elements in the buildings' façades. The use of cultural references, such as the song *We are free* [Somos Livres] by singer Ermelinda Duarte, substantiate the notion that learning can be facilitated by establishing a correlation between artistic expression and historical and social transformation. The game fosters interdisciplinary learning across subjects such as history, geography, citizenship, mathematics, and visual arts.

- *Art Nouveau Path*

The game was developed for students in the 3rd CBE, secondary school students, tourists, and the general community. Promoting ESD is the objective of this game, which encourages students to explore Aveiro's Art Nouveau heritage. The emphasis is on both the aesthetic qualities and the cultural and historical significance of this heritage. The game sheds light on the artistic movement's contribution to the city's identity, provoking contemplation on the significance of safeguarding cultural heritage. The path begins at Melo Freitas Square, passes by the Monument to Liberty, and then returns to Melo Freitas Square at the former location of the Ala Pharmacy. It continues along João Mendonça Street, including stops at the former Agricultural Cooperative and the City Museum. The path continues along Dr. Barbosa de Magalhães Street to the Art Nouveau Museum, then proceeds to José Estêvão Market and 'Fish Market' [Praça do Peixe], concluding at Tenente Resende Street in proximity to the 'Pensão Ferro'. This game, which comprises 36 questions, integrates content from various subjects, including Portuguese, mathematics, natural sciences, physical and chemical sciences, history, geography, foreign languages, visual education, and citizenship. In addition, it promotes critical thinking about the preservation of urban identity and the role of art in the formation of cultural memory, linking artistic heritage to education for sustainability.

- *Aveiro Walking Tour*

The game was developed for secondary and university students, tourists, and the general public. The game's objective is to promote ESD by encouraging critical reflection on democratic values, civic participation, and the role of public spaces and memory in shaping a sense of collective identity. By engaging with iconic locations across the city,

players are encouraged to explore the links between heritage, citizenship, and freedom. The game starts at the University Rectory and ends in the bridges area, in the city centre. The path is punctuated by nine points of interest, including the University Rectory, the Old University Rectory, the Infante D. Pedro Park Cave, the Infante D. Pedro Park Bandstand, the Santa Joana de Aveiro Museum, Santa Joana Park, and the Statues on the Bridges area. A total of 25 questions are included in the game, with feedback comprising a variety of educational resources on subjects including mathematics, natural sciences, history, visual education, citizenship, environmental education, and trivia about the city, its traditions, and its natural and built heritage. Participants are invited to reflect on the past and present significance of civic spaces, thereby fostering deeper engagement with cultural heritage and democratic values in a meaningful and participatory way.

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