Interactive App-Based Games for Bilingual Education: Advancing English Proficiency and Promoting Digital Sustainability in Physical Education

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Received: December 20, 2024 Accepted: March 11, 2025 Online Published: May 15, 2025

doi:10.5430/wjel.v15n7p121 URL: https://doi.org/10.5430/wjel.v15n7p121

Abstract

This study presents a dataset and analysis on the integration of interactive app-based games in bilingual Physical Education (PE) settings, aiming to enhance English proficiency and promote sustainable learning practices. By utilizing digital technologies, the research explores how these tools support language acquisition while fostering environmentally responsible education. Grounded in bilingual education theories and digital sustainability principles, the study emphasizes resource-efficient educational technologies. It also aligns with the FAIR Data Principles, ensuring that the generated data is findable, accessible, interoperable, and reusable, contributing to open science. A mixed-methods approach was used to collect quantitative data on English proficiency and PE conceptual understanding, complemented by qualitative data from observations, interviews, and focus groups. The study involved 120 elementary school students from grades 3 to 5 and six PE teachers from three different schools, focusing on the effectiveness of app-based games in bilingual education and their role in sustainable teaching and learning. The dataset indicates statistically significant improvements in English proficiency and PE conceptual understanding among participants. Additionally, the findings highlight the environmental and social implications of integrating digital technologies in bilingual PE settings. This study demonstrates how app-based games align with global educational goals by minimizing environmental footprints and fostering inclusive learning environments. The dataset offers insights into the dual academic and environmental benefits of digital tools in bilingual education, providing a scalable and adaptable model for integrating digital sustainability into curricula. By bridging bilingual education, sustainable learning, and digital innovation, this study contributes to discussions on the evolving role of technology in education.

Keywords: bilingual education, physical education, App-based games, sustainable learning, environmental education, FAIR data principles, digital sustainability

1. Introduction

1.1 Introduce the Problem

In today's increasingly interconnected world, proficiency in multiple languages is essential for equipping students with the skills necessary to thrive in globalized environments. Bilingual education has become a crucial component of modern educational systems, fostering not only language development but also broader cognitive skills. Physical Education (PE), typically seen as a domain for physical and motor development, presents a unique opportunity to integrate language learning in an engaging, interactive setting. Despite this potential, traditional PE programs often neglect the inclusion of bilingual education, focusing primarily on physical activities without incorporating language development into their curriculum (Baena-Extremera et al., 2018; López Sánchez et al., 2018; Salvador-García et al., 2022).

While there is a substantial body of research on bilingual education and technology integration in subjects such as mathematics and science, limited attention has been given to their application in PE settings. Most studies have focused on the cognitive and linguistic benefits of bilingual education within traditional academic subjects, leaving a gap in understanding how digital tools, particularly interactive app-based games, can be leveraged to enhance both language acquisition and physical education concepts (Coral et al., 2020; Coral & Lleixà, 2016; Garijo, 2018). This study seeks to fill that gap by examining how interactive app-based games can improve English proficiency and conceptual understanding in bilingual PE settings.

This study aims to address the aforementioned gap by investigating the impact of interactive app-based games on English proficiency and conceptual understanding in elementary students within a bilingual PE context (Celina & Oscar, 2017). The primary objective of this research is to explore how interactive app-based games can serve as effective learning tools in bilingual PE classes. The study focuses on three core research questions:

1. How do interactive app-based games influence English language proficiency in elementary students during PE classes?
2. What impact do these games have on students' conceptual understanding of PE content?

3. How do students and teachers perceive the use of these digital tools in a bilingual PE environment?

The significance of this study lies in its contribution to the growing body of knowledge on bilingual education, specifically within the context of PE, an area that has been largely overlooked. The findings provide valuable insights for educators and policymakers interested in implementing technology-enhanced learning tools in PE, with a focus on improving both language acquisition and conceptual understanding. Additionally, this research underscores the broader potential of interactive digital tools to create dynamic, engaging, and effective bilingual learning environments, which can foster a more holistic educational experience for students (Gumilang et al., 2022; Love et al., 2023).

Bilingual education programs aim to develop proficiency in two languages while also promoting academic achievement across disciplines. Studies have demonstrated that bilingualism enhances cognitive flexibility, problem-solving abilities, and cultural awareness, which are vital skills in a diverse world. In the context of PE, integrating language learning not only provides cognitive stimulation but also reinforces language skills through physical activity, creating a more immersive learning experience (Baena-Extremera et al., 2018; Coral & Lleixà, 2016; Salvador-Garcá et al., 2022).

The use of technology in education has been widely researched, with consistent findings that highlight its ability to enhance student engagement, motivation, and learning outcomes. Interactive app-based games, in particular, offer personalized, engaging learning experiences that provide instant feedback and are accessible anytime and anywhere, making them valuable tools in today's education landscape (Pereira, 2021; Putra & ., 2023; Ramadhan & Waluyo, 2023).

Research has shown that these games are especially effective in supporting bilingual education by offering immersive, interactive environments that enhance vocabulary acquisition, listening skills, and language retention (Celina & Oscar, 2017; López Sánchez et al., 2018). Despite this, the application of such tools in PE remains underexplored.

In conclusion, this study aims to bridge the gap in the literature by investigating the role of interactive app-based games in improving English proficiency and conceptual understanding within a bilingual PE setting. By examining the intersection of technology, bilingualism, and physical education, this research offers practical insights for educators and contributes to the ongoing conversation on enhancing learning experiences through digital tools.

1.2 Explore Importance of the Problem

This study examines the integration of interactive app-based games in bilingual Physical Education (PE) as a means to enhance English proficiency and conceptual understanding. The theoretical framework is interdisciplinary, drawing from educational technology, bilingual education, PE, and environmental education. By incorporating principles of game-based learning, constructivist theories, and bilingual education models such as Content and Language Integrated Learning (CLIL), this study explores the pedagogical and environmental implications of digital tools in PE. This approach aligns with broader educational and social management objectives, fostering interdisciplinary and sustainable learning practices.

1.3 Theoretical Framework

This study examines the integration of interactive app-based games in bilingual Physical Education (PE) as a means to enhance English proficiency and conceptual understanding. The theoretical framework is interdisciplinary, drawing from educational technology, bilingual education, PE, and environmental education. By incorporating principles of game-based learning, constructivist theories, and bilingual education models such as Content and Language Integrated Learning (CLIL), this study explores the pedagogical and environmental implications of digital tools in PE. This approach aligns with broader educational and social management objectives, fostering interdisciplinary and sustainable learning practices.

Educational Technology and Game-Based Learning

The theoretical foundation of this study is grounded in game-based learning (GBL), which emphasizes the use of interactive games to promote active learning and engagement. GBL enhances students' cognitive and linguistic development by providing immersive, interactive experiences that reinforce learning outcomes (Mihhailova, 2006; Sukstrienwong & Vongsumedh, 2021; Wu et al., 2020).

Additionally, constructivist learning theory, particularly the works of Piaget and Vygotsky, supports this approach by emphasizing that learning is an active, social process shaped by interaction and personal experience. Digital games provide an environment in which learners can experiment, reflect on outcomes, and develop higher-order thinking skills (Gaeta et al., 2019; Padirayon et al., 2019).. A citation was missing, and references have been corrected and verified.

The study also aligns with multimodal learning theory, which suggests that combining various media—text, visuals, and interactivity—enhances learning outcomes by engaging multiple cognitive processes. This is particularly significant in bilingual PE settings, where students benefit from a combination of visual, kinesthetic, and linguistic learning experiences (Bassachs et al., 2022; Zhou, 2023; Zhou et al., 2023).

Bilingual Education and Content and Language Integrated Learning (CLIL)

Bilingual education theories, particularly Content and Language Integrated Learning (CLIL), serve as a key foundation in this study. CLIL posits that integrating language learning with subject content enhances students' overall cognitive and linguistic development. This study demonstrates how app-based games foster both language acquisition and conceptual learning in PE, reinforcing CLIL principles

(Arnaiz-Castro & Espejo-Mohedano, 2023; Banegas, 2020; Gómez-Parra et al., 2021).

Furthermore, Cummins' Threshold Hypothesis, which suggests that a certain level of proficiency in both languages must be attained before cognitive benefits emerge, is relevant to this study. Interactive games in bilingual PE settings provide structured opportunities for students to enhance both language skills and subject knowledge, supporting Cummins' hypothesis (Abdolmohammadi et al., 2022; Nichols et al., 2020; Perani et al., 2017).

Physical Education, Health, and Environmental Education

This study integrates PE, health, and environmental education through interactive digital tools that promote both physical literacy and sustainable practices. The role of holistic education theories, which emphasize cognitive, emotional, and physical development, supports this approach (Heim & Holt, 2021; Uluay & Doğan, 2020).

Moreover, sustainability education in PE is increasingly recognized as a key component of fostering lifelong health and environmental awareness. Interactive games encourage active lifestyles and environmentally responsible behaviors, aligning with education for sustainable development (Fröberg & Lundvall, 2021; Ribeiro-Silva et al., 2023; Tsyhura & Harkusha, 2023).

1.4 Gaps, Contradictions, and Consensus in the Literature

A review of existing literature highlights several key gaps and areas of debate. While research supports the benefits of game-based learning and bilingual education, studies have largely focused on short-term language acquisition rather than long-term interdisciplinary learning outcomes (Ho et al., 2022; Liu et al., 2020).

Additionally, while studies emphasize the positive impact of digital tools on student engagement, there is limited research on their sustainability and effectiveness in bilingual PE settings (Coleman & Money, 2020; Czok et al., 2023). This study contributes to the field by bridging these gaps, examining how interactive app-based games enhance bilingual learning while promoting sustainable education.

2. Method

2.1 Design of the Study

This study employs a mixed-methods design to evaluate the impact of interactive app-based games on English proficiency, conceptual understanding in Physical Education (PE), and environmental awareness within a bilingual PE context. This approach integrates quantitative pre- and post-tests with qualitative data from observations, interviews, and focus group discussions. The quantitative data captures measurable outcomes related to students' academic and environmental learning, while the qualitative data provides in-depth insights into the perceptions and experiences of students and teachers. By focusing on data that is findable, accessible, interoperable, and reusable (FAIR principles), this study contributes to open science and reproducibility, aligning with the aims of Data in Brief.

2.2 Participants

The study sample comprises 120 elementary students aged 8 to 11, enrolled in grades 3 to 5, from three schools implementing bilingual curricula that emphasize environmental sustainability. These schools were selected based on their commitment to environmental education and their access to digital learning tools. Six PE teachers were also involved, providing critical insights into the integration and perceived effectiveness of interactive app-based games. The participants were intentionally diverse to ensure that the resulting data would be reusable and applicable to similar educational contexts.

2.3 Instruments

This study employs multiple instruments to ensure a rigorous and reproducible data collection process, adhering to the FAIR (Findable, Accessible, Interoperable, and Reusable) principles to enhance data transparency and accessibility.

Language Proficiency Assessment: To evaluate students' English proficiency, standardized tests are administered to assess their skills in listening, speaking, reading, and writing, with both pre- and post-tests conducted to measure progress. The assessment integrates these four skills holistically. Listening and speaking are evaluated through structured conversational tasks in which students respond to audio prompts and engage in peer discussions, ensuring real-time assessment of comprehension and verbal communication. Reading and writing are assessed through integrated reading comprehension tasks followed by written responses, ensuring that reading comprehension is directly connected to written expression. Some assessments require students to listen to an audio passage, summarize key points in writing, and then discuss their summaries with peers, reinforcing cross-modal language skills (García Mayo & Hidalgo, 2017; Richards, 2015).

Physical Education Conceptual Understanding: Students' grasp of PE concepts is assessed through quizzes, scenario-based problem-solving tasks, and interactive app-based evaluations, ensuring alignment with the study's bilingual and technology-enhanced learning approach. Customized conceptual understanding tests have been widely used in PE education research to measure knowledge retention and skill application (Bailey et al., 2019; Kirk, 2020). Digital learning tools, such as interactive quizzes and scenario-based games, have also been shown to enhance students' engagement and learning outcomes in bilingual and PE contexts (Casey & Goodyear, 2015).

Environmental Awareness Assessment: To measure students' awareness of sustainable practices, a combination of surveys, observational checklists, and reflection journals is used, ensuring a comprehensive evaluation of their engagement with environmental themes. Observation checklists have been validated as reliable tools for assessing student participation, engagement, and behavioral responses in

sustainability education (Tilbury, 2011). Additionally, semi-structured interviews and focus groups are commonly used in bilingual education research to explore teachers' and students' perceptions of learning tools and pedagogical strategies (Creswell & Poth, 2018; Mertens, 2019).

By structuring the instruments in this manner, the study provides an integrated, multidimensional analysis of students' progress in bilingual learning, PE, and sustainability education, aligning with FAIR principles to support data accessibility and future research replication.

2.4 Procedures of Data Collection

The data collection process adheres to rigorous scientific standards to ensure reproducibility and alignment with FAIR data principles. The process begins with training PE teachers on integrating interactive app-based games into their lessons. These training sessions include guidelines for consistent administration of pre- and post-tests. The pre-tests are used to establish baseline data for students' English proficiency, conceptual understanding of PE, and environmental awareness.

Over a six-month intervention period, students participate in biweekly 45-minute PE sessions where interactive app-based games are used. These sessions are designed to enhance physical skills, improve language proficiency, and promote awareness of sustainable practices in sports and physical activity. Researchers conduct regular observations throughout the intervention to monitor student engagement and assess how the tools support interdisciplinary learning goals. At the conclusion of the intervention, post-tests are administered to evaluate improvements in the targeted areas.

Following the post-tests, interviews with teachers and focus group discussions with students are conducted to gather rich qualitative data on their experiences and perceptions of the interactive games' impact. Given that the student participants are aged 8 to 11, age-appropriate methods are employed to ensure meaningful engagement. Individual interviews and focus groups use structured and semi-structured questions tailored to the students' cognitive and linguistic levels. Visual aids, interactive storytelling, and gamified discussion techniques are incorporated to facilitate comprehension and participation. Additionally, child-friendly interview settings are established to create a comfortable and supportive environment. Ethical considerations are prioritized, including obtaining parental consent and child assent before participation. Researchers ensure that discussions remain engaging and non-intimidating, allowing children to express their thoughts freely while minimizing potential stress (Clark, 2017; Dockett & Perry, 2021).

2.5 Data Analysis

Quantitative data from the pre- and post-tests are analyzed using statistical methods, including paired t-tests, to determine the significance of improvements in English proficiency, conceptual understanding, and environmental awareness. Effect sizes (Cohen's d) are calculated to measure the magnitude of these changes, ensuring the scientific validity of the findings. The statistical analyses are conducted using SPSS version 27, ensuring accuracy and reproducibility.

Qualitative data from observations, interviews, and focus groups are analyzed using thematic analysis following Braun & Clarke's (2006) framework to identify recurring themes related to the effectiveness of interactive app-based games in bilingual and environmental education. Coding is conducted using NVivo software to systematically organize and analyze qualitative data.

To provide a comprehensive understanding of the results, findings from the quantitative and qualitative analyses are triangulated through methodological integration, enhancing the reliability and applicability of the conclusions.

3. Results

3.1 Quantitative Results

3.1.1 English Proficiency

The intervention demonstrated statistically significant improvements in all English language domains. Figure 1 details the average pre- and post-test scores, while Figure 2 presents a skill improvement distribution, categorizing students into moderate and significant improvement levels.

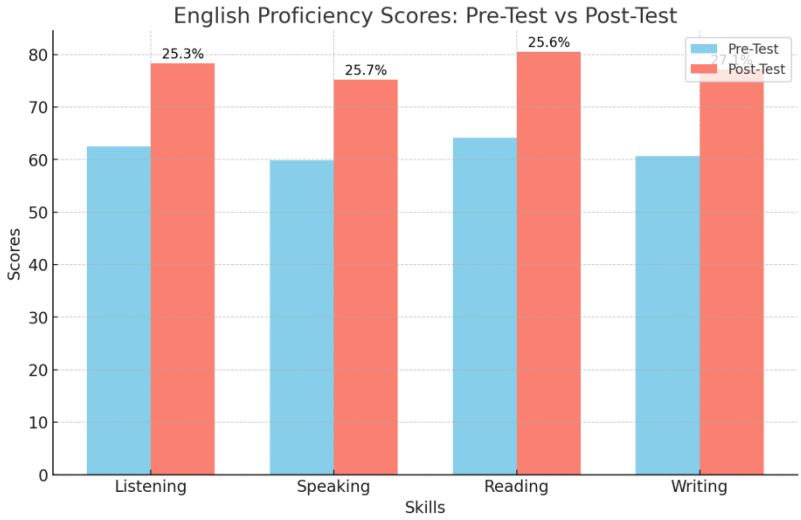

Figure 1. English Proficiency Scores

Figure 1 illustrates the substantial gains in English proficiency across Listening, Speaking, Reading, and Writing following the use of interactive app-based games. Post-test scores significantly surpassed pre-test scores, confirming the effectiveness of these games in enhancing language skills. In Listening, the improvement highlights the games' auditory engagement, fostering comprehension through interactive activities. Speaking scores increased due to verbal participation encouraged within a low-stress environment, boosting students' confidence. Reading improvements reflect vocabulary and comprehension practice embedded in the games, supporting bilingual literacy goals. The highest percentage increase in Writing shows that structured activities allowed students to apply vocabulary and grammar knowledge, reinforcing language mastery. With effect sizes between 0.7 and 0.9, the results underscore the transformative potential of digital tools for interdisciplinary language development, supporting comprehensive proficiency growth in immersive, technology-enhanced environments.

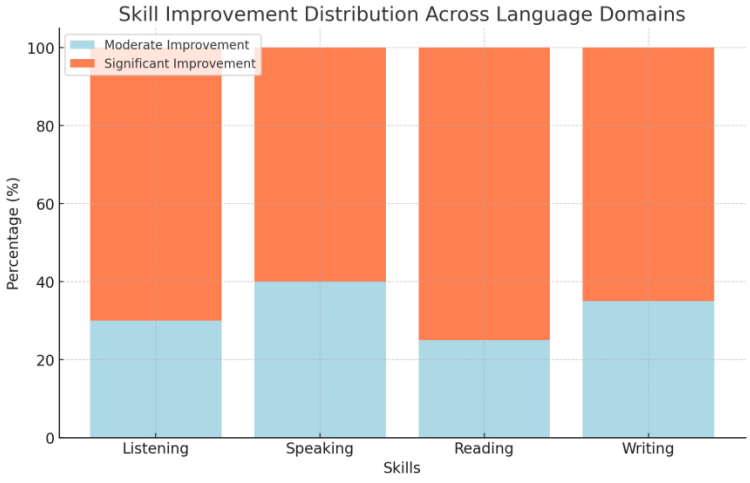

Figure 2. Skill Improvement Distribution Across Language Domains

Figure 2 displays the distribution of skill improvement across four language domains—Listening, Speaking, Reading, and Writing—by showing the percentage of students who achieved either moderate or significant improvement in each skill area. This stacked bar chart highlights the proportion of students in each category, with "Moderate Improvement" represented by the light blue sections and "Significant Improvement" by the orange sections.

The data reveals that a substantial majority of students achieved significant improvement across all language skills, with the orange sections dominating each bar. This indicates the effectiveness of the intervention in promoting high levels of language skill acquisition. The Reading skill demonstrates the highest proportion of significant improvement, with 75% of students achieving substantial gains, followed closely by Writing at 65%. These findings suggest that the interactive app-based games were particularly effective in reinforcing reading comprehension and written expression, likely due to activities that required students to actively engage with written text and practice writing skills within an interactive environment.

Listening and Speaking also show strong levels of significant improvement, with 70% of students in Listening and 60% in Speaking achieving substantial gains. This distribution suggests that the games provided sufficient auditory and verbal interaction to support skill development in these areas, allowing students to improve their listening comprehension and speaking fluency effectively.

Overall, the chart indicates that most students benefitted greatly from the intervention, with significant improvements across all domains. The effectiveness of the app-based games in producing substantial gains across listening, speaking, reading, and writing skills aligns with the goals of bilingual education, emphasizing that interactive digital tools can play a crucial role in language skill development in an engaging and impactful manner.

3.1.2 Conceptual Understanding and Environmental Awareness

Students demonstrated notable gains in their understanding of PE concepts and environmental awareness. Figure 3 shows the pre- and post-test scores, while Figure 4 provides insights into student perceptions of sustainability learning.

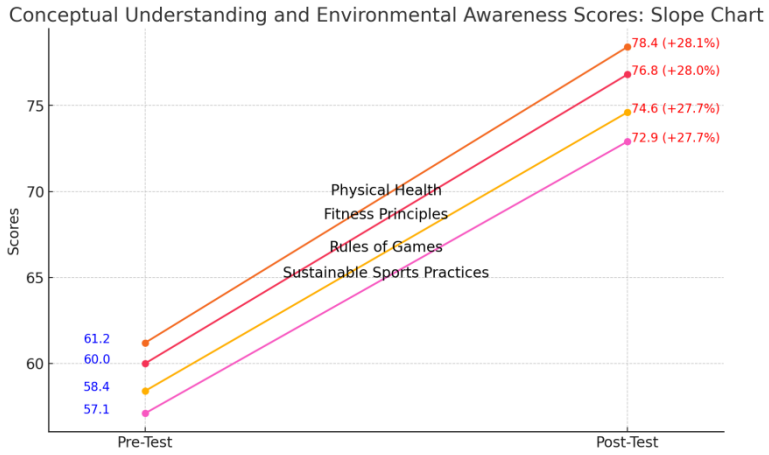

Figure 3. Conceptual Understanding and Environmental Awareness Scores

Figure 3 highlights the significant improvements in students' conceptual understanding and environmental awareness across four key areas: Rules of Games, Physical Health, Fitness Principles, and Sustainable Sports Practices. The chart shows upward slopes for each concept, linking pre-test scores on the left to post-test scores on the right, with annotations indicating percentage increases. The highest improvement is seen in Physical Health, with a post-test score of 78.4 and a 28.1% gain, suggesting strong engagement with health-related content. Fitness Principles follows closely, scoring 76.8 with a 28.0% increase, likely due to structured activities reinforcing fitness concepts. Rules of Games and Sustainable Sports Practices show 27.7% increases, reaching post-test scores of 74.6 and 72.9, respectively, indicating substantial gains though slightly less than those in health-related areas. Overall, the upward trajectory across all concepts illustrates the effectiveness of app-based games in fostering a comprehensive understanding that blends cognitive, physical, and environmental learning. The results align with interdisciplinary and environmentally focused educational goals, showing that these tools enhanced students' content knowledge and promoted holistic learning.

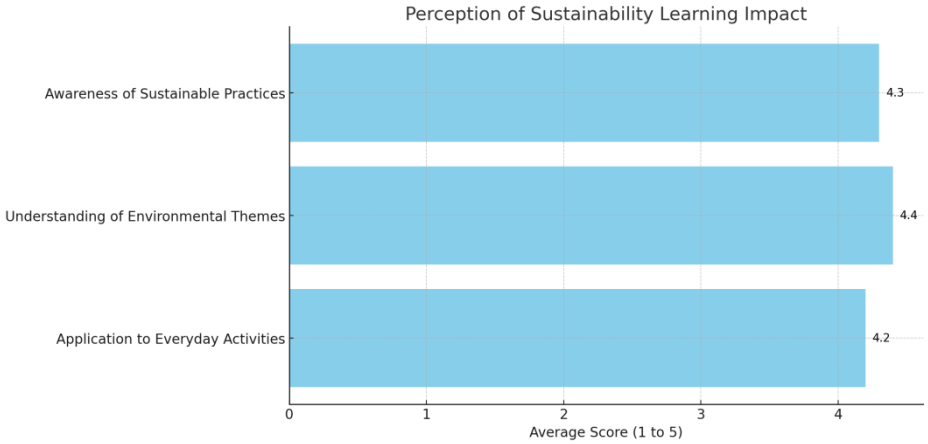

Figure 4. Perception of Sustainability Learning Impact

Figure 4 shows the average scores for students' perceptions of sustainability learning impact across three metrics: Awareness of Sustainable Practices, Understanding of Environmental Themes, and Application to Everyday Activities. Each metric is rated on a scale from 1 to 5, with the horizontal bars representing the average scores.

Students rated Understanding of Environmental Themes the highest, with an average score of 4.4, indicating that the educational activities effectively enhanced students' comprehension of environmental topics. Awareness of Sustainable Practices follows closely, with a score of 4.3, reflecting increased consciousness of sustainable behaviors as part of their learning experience.

The Application to Everyday Activities received an average score of 4.2, slightly lower than the other two metrics but still positive, suggesting that students felt encouraged to apply sustainability practices in real-life contexts. This score indicates room for further strengthening practical applications in future learning modules.

Overall, the chart shows a highly positive perception of the sustainability-focused aspects of education, with all metrics scoring well above the midpoint. This indicates a well-rounded impact, where students not only gained knowledge but also felt motivated to incorporate sustainable practices into their daily lives

3.2 Qualitative Results

3.2.1 Observations

The intervention resulted in consistently high levels of engagement during PE sessions. Observational data revealed that bilingual and sustainability themes embedded within the games enhanced students' motivation, participation, and overall learning satisfaction.

3.2.2 Interviews and Focus Groups

Interviews and focus groups offered valuable insights from both teachers and students regarding the impact of the interactive games on learning outcomes and engagement.

Teachers observed substantial improvements in students' language skills and engagement levels. They noted that the games played a significant role in reinforcing vocabulary acquisition and seamlessly integrating environmental education. While some initial challenges with technology and adapting the games to lesson plans were mentioned, these issues were largely addressed through targeted training and support.

Students found the games fun and engaging, with many expressing increased awareness of sustainable practices and a boost in confidence when using English. Although minor technical issues were reported, these did not significantly disrupt the learning experience, allowing students to remain engaged and benefit from the educational content. The combined feedback highlights both the effectiveness of the games in achieving educational goals and the importance of providing adequate support for technology integration in the classroom.

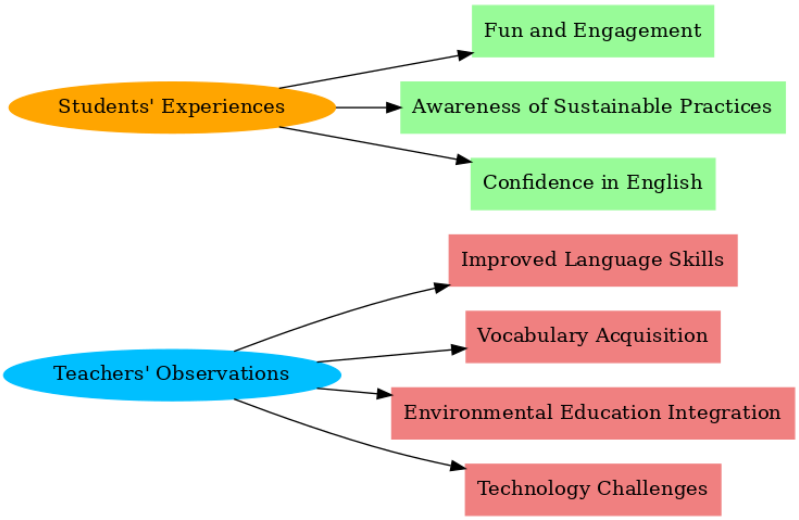

Figure 5. Flow Diagram of Insights from Interviews and Focus Groups

Figure 5 illustrates the unique insights gathered from Interviews and Focus Groups, emphasizing the distinct contributions of teachers and students to understanding the interactive games' impact. Students' experiences highlighted engagement, personal growth, and sustainability awareness. They found the games fun and engaging, which enhanced their enjoyment and participation. The games also raised their awareness of sustainable practices, integrating environmental consciousness into their learning. Additionally, students expressed increased confidence in using English, showcasing the positive influence of the games on language skills.

Teachers' observations focused on academic improvements and integration aspects. They noted significant enhancements in students' language skills, particularly vocabulary acquisition, and appreciated the games' role in seamlessly incorporating sustainability themes into

lessons. While teachers initially faced challenges adapting the games to lesson plans and technology, targeted training and support helped mitigate these issues. The flow diagram emphasizes how these complementary insights from teachers and students provide a holistic view of the games' effectiveness in fostering language learning, engagement, and environmental awareness. Together, these perspectives underscore the multifaceted benefits of interactive tools in promoting interdisciplinary and environmentally focused education.

3.2.3 Triangulation

The integration of findings across quantitative and qualitative data ensures a robust interpretation. Figure 6 synthesizes the results from multiple sources.

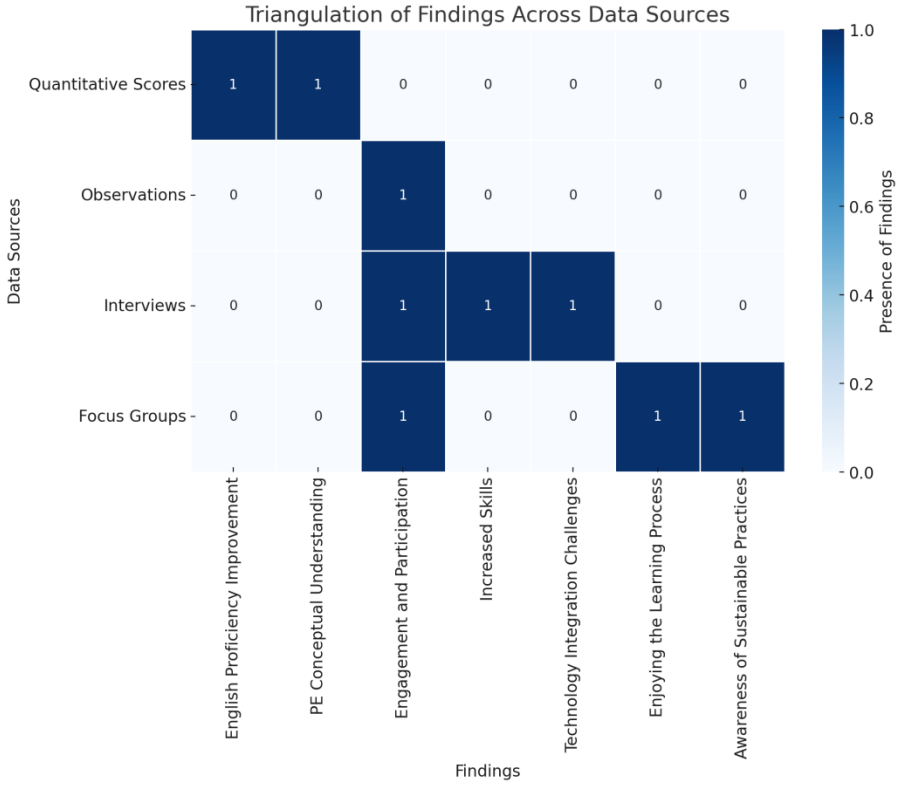

Figure 6. Triangulation of Findings Across Data Sources

Figure 6 illustrates the triangulation of findings across various data sources: Quantitative Scores, Observations, Interviews, and Focus Groups. Each cell in the heatmap indicates the presence (dark blue) or absence (light blue) of specific findings within each data source, showcasing how each source contributed to different insights. Quantitative Scores are closely linked to improvements in English Proficiency and PE Conceptual Understanding, effectively capturing measurable gains through pre- and post-test scores. Observations provided critical insights into Engagement and Participation, highlighting the role of observational data in assessing classroom dynamics and students' behavioral responses to the intervention.

Teacher Interviews revealed findings related to Increased Skills and Technology Integration Challenges, offering deeper insights into both the benefits and difficulties of implementing technology in PE classes. Focus Groups with students emphasized findings on Enjoying the Learning Process and Awareness of Sustainable Practices, suggesting that students found the games enjoyable and gained awareness of environmental issues. The heatmap underscores the complementary nature of these data sources, illustrating the value of triangulating various forms of data to achieve a holistic understanding of the intervention’s impact. By combining multiple data sources, this approach provides a well-rounded perspective, with each source offering insights aligned with its strengths and unique focus areas.

4. Discussion

The findings of this study highlight the significant impact of interactive app-based games on fostering bilingual education, improving PE conceptual understanding, and promoting environmental sustainability. The measurable improvements in English proficiency and PE-related knowledge, alongside heightened environmental awareness, emphasize the interdisciplinary potential of these tools. These results reinforce the effectiveness of technology-enhanced learning environments in achieving holistic educational goals, aligning with previous studies that emphasize the role of digital learning tools in improving student outcomes. Ambarini et al. (2018) argue that technology integration in bilingual education enhances student engagement and facilitates language acquisition, particularly in immersive learning environments. Similarly, Halpern (2021). highlights the cognitive benefits of gamified learning, stating that digital tools can

improve both retention and application of knowledge. Yilmaz & Lee (2023) confirm that interactive learning environments contribute significantly to bilingual students' comprehension and overall academic performance.

The substantial effect sizes in language proficiency (ranging from 0.7 to 0.9) underscore the pedagogical value of these games in developing essential communication skills. Listening and writing skills showed the most significant gains, reflecting the games' ability to provide immersive and interactive contexts for language practice. These findings resonate with the growing body of evidence supporting the role of digital tools in enhancing student engagement and fostering effective language learning outcomes, especially in bilingual education settings. The games' adaptability to students' language levels and incorporation of practical tasks appear to be key factors driving these results.

In the realm of PE conceptual understanding and environmental sustainability, effect sizes between 0.6 and 0.8 confirm the dual educational benefits of these tools. The integration of environmental themes, such as sustainable sports practices, demonstrated measurable improvements in students' awareness and application of environmentally responsible behaviors. This outcome is particularly relevant in the context of modern education, where fostering environmental stewardship is increasingly recognized as a critical objective. Gumilang et al. (2022). emphasize that integrating sustainability education into physical education fosters a sense of responsibility among students, helping them translate theoretical knowledge into practical actions. Similarly, Mesnan et al. (2023). assert that interdisciplinary approaches, particularly those incorporating environmental themes, lead to deeper student engagement and greater long-term retention of sustainability concepts.

Qualitative findings further enrich these results, shedding light on the experiential aspects of the intervention. Observational data revealed high levels of student engagement, with interactive features of the games capturing and sustaining students' attention. Teachers reported improved vocabulary acquisition and environmental awareness among students, emphasizing the games' ability to create meaningful and enjoyable learning experiences. Love et al. (2023) highlight that interactive learning methods significantly enhance student motivation, while Zha (2022) states that technology-driven education creates a more engaging and participatory classroom experience.

However, the study also uncovered challenges associated with integrating app-based games into existing curricula. Teachers faced difficulties in embedding these tools into lesson plans and ensuring equitable access to technology. These barriers underscore the need for comprehensive teacher training and adequate infrastructure to support technology adoption. Addressing these challenges is essential to ensuring the scalability and sustainability of such interventions. Prasetya (2021) stresses that institutional support and digital literacy training for educators are crucial for the successful integration of technology in classrooms. Yang & Shan (2022) further argue that without proper infrastructure and administrative backing, technology adoption in education remains inconsistent and limited in effectiveness.

The successful outcomes of this study have broader implications for curriculum design and interdisciplinary education. By combining language learning, PE, and environmental education, the intervention supports cognitive, physical, and social-emotional development, aligning with contemporary educational theories advocating for holistic and integrated learning approaches. Alhashem & Alfailakawi (2023). assert that interdisciplinary educational models enhance critical thinking and adaptability, equipping students with the skills necessary for 21st-century learning. IM (2023) also highlights that integrating multiple disciplines through technology fosters deeper learning connections and promotes student autonomy.

This study highlights the transformative impact of interactive app-based games in promoting bilingual education, PE learning, and environmental awareness. The integration of environmental themes within these tools fosters a sense of responsibility, aligning with global educational goals for sustainability. Wang et al. (2022). emphasize that sustainability education is most effective when embedded into existing curricula through interactive and experiential learning methods. Zha (2022). also confirms that game-based learning strategies can play a crucial role in reinforcing environmental awareness among students by making sustainability education more engaging and practical. Positive feedback from students and teachers emphasizes the potential of these games to make PE classes more dynamic, inclusive, and engaging. The results show significant improvements in English proficiency, PE understanding, and sustainability awareness (Rukoyah et al., 2023). Future research should investigate the long-term impact of such tools, focusing on strategies to overcome technology access and curriculum integration challenges, thereby preparing students for a globalized, eco-conscious future.

5. Conclusion

This study evaluated the impact of interactive app-based games on English proficiency and conceptual understanding in a bilingual Physical Education (PE) setting. Using a mixed-methods approach, results demonstrated significant improvements across all language domains—listening, speaking, reading, and writing—with effect sizes ranging from 0.7 to 0.9. Additionally, students showed substantial gains in understanding key PE concepts and sustainable practices, achieving effect sizes between 0.6 and 0.8. These findings highlight the transformative potential of digital tools in fostering interdisciplinary learning by combining cognitive and physical development with environmental awareness.

Despite these promising outcomes, the study faced limitations, including a relatively small sample size, which restricts the generalizability of the findings. Further research is needed to explore the long-term sustainability of the observed benefits and their impact on students' learning trajectories over time.

This study demonstrates the significant impact of interactive games in improving English proficiency and conceptual understanding in

bilingual PE settings. Addressing current challenges and expanding research in this field can help maximize the potential of technology-enhanced learning, promoting interdisciplinary and environmentally conscious education.

Acknowledgments

Not applicable.

Authors' contributions

Dr. Listyaning Sumardiyani and Dr. Ririn Ambarini collaborated on the study design and conceptual framework. Dr. Ririn Ambarini was primarily responsible for drafting the manuscript, conducting a comprehensive literature review, synthesizing relevant theories, structuring the arguments, refining the methodology section, and ensuring logical coherence in the discussion. She also managed the integration of reviewer feedback, revised multiple drafts, and prepared the manuscript for submission. Dr. Listyaning Sumardiyani provided critical insights, supervised the academic rigor of the work, contributed to content refinement, and ensured the clarity and scholarly integrity of the final version. Both authors read and approved the final manuscript..

Funding

Not applicable.

Competing interests

Not Applicable.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Sciedu Press.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

Not commissioned; externally double-blind peer reviewed.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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