Effects of an AI-supported movement-based Physical Education program using a virtual nature reserve on ecological literacy and inquiry skills

Efectos de un programa de Educación Física basado en el movimiento y apoyado por Inteligencia Artificial mediante una reserva natural virtual sobre la alfabetización ecológica y las habilidades de indagación

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Abstract

Introduction: Contemporary Physical Education (PE) reform promotes cognitively engaging movement and holistic student development. However, sustainability education in secondary schools remains largely classroom-centered, limiting embodied ecological learning within PE contexts.
Objective: This study examined the effects of an Artificial Intelligence (AI)–supported movement-based PE program using a Virtual Nature Reserve (VNR) on ecological literacy and inquiry skills among secondary school students.
Methodology: A quasi-experimental pretest–posttest control group design involved 126 students (M_age = 16.2 ± 0.7 years) assigned to three groups: AI-supported movement-based PE (n = 42), inquiry-based multimedia instruction (n = 41), and conventional teaching (n = 43). The eight-week intervention was implemented during 90-minute PE sessions. Movement intensity varied across phases, with eco-circuit activities approximating moderate intensity (around 3–5 METs). Data were analyzed using ANCOVA with pretest scores as covariates.
Results: Significant differences were found in ecological literacy (η^2p = .29) and inquiry skills (η^2p = .24), favoring the experimental group.
Conclusions: The movement-integrated PE model may enhance ecological literacy and inquiry skills while maintaining moderate physical engagement and complementing Outdoor Education approaches.

Keywords

Physical Education; ecological literacy; inquiry skills; artificial intelligence; movement-based learning; secondary education; outdoor education.

Resumen

Introducción: La reforma de la Educación Física (EF) contemporánea promueve el movimiento cognitivamente atractivo y el desarrollo holístico del alumnado. Sin embargo, la educación para la sostenibilidad en la educación secundaria sigue estando mayormente centrada en el aula, lo que limita el aprendizaje ecológico corporal en contextos de EF.
Objetivo: Este estudio examinó los efectos de un programa de EF basado en el movimiento con apoyo de Inteligencia Artificial (IA), utilizando una Reserva Natural Virtual (RNV), sobre la alfabetización ecológica y las habilidades de indagación en alumnado de secundaria.
Metodología: Un diseño cuasiexperimental de grupo control pretest-postest incluyó a 126 alumnas (edad media = 16,2 ± 0,7 años) asignadas a tres grupos: EF basada en el movimiento con apoyo de IA (n = 42), instrucción multimedia basada en la indagación (n = 41) y enseñanza convencional (n = 43). La intervención, de ocho semanas de duración, se implementó en sesiones de EF de 90 minutos. La intensidad del movimiento varió entre las fases, con actividades de ecocircuito de intensidad moderada (alrededor de 3-5 MET). Los datos se analizaron mediante ANCOVA con las puntuaciones del pretest como covariables. Resultados: Se encontraron diferencias significativas en la alfabetización ecológica (η^2p = .29) y las habilidades de indagación (η^2p = .24), a favor del grupo experimental.
Conclusiones: El modelo de EF integrado en el movimiento puede mejorar la alfabetización ecológica y las habilidades de indagación, manteniendo una actividad física moderada y complementando los enfoques de Educación al Aire Libre.

Palabras clave

Educación Física; alfabetización ecológica; habilidades de indagación; inteligencia artificial; aprendizaje basado en el movimiento; educación secundaria; educación al aire libre.

Introduction

Contemporary Physical Education (PE) is undergoing significant reform, shifting from a traditional focus on motor performance and physical fitness toward broader educational goals that include cognitive engagement, social development, and interdisciplinary learning (Pla-Pla, Lavega-Burgués & Sáez de Ocáriz Granja, 2025; Li & Zhang, 2024; Siedentop & Van der Mars, 2022). Recent sport pedagogy frameworks emphasize that PE should not be confined to physical competence alone, but rather function as a holistic educational space promoting decision-making, problem-solving, cooperation, and reflective thinking (Dyson, Griffin & Hastie, 2004). Within this reform movement, PE is increasingly recognized as a context for meaningful learning experiences that integrate movement with intellectual and socio-emotional development (Jadwiszczak, Wawrzyniak & Pezdek, 2025).

This reconceptualization aligns with the notion of physically educated individuals who demonstrate not only motor proficiency but also critical thinking and responsible behavior (Chen, 2022). As a result, PE curricula are expanding to incorporate cognitively engaging tasks, tactical understanding, and real-world applications of movement (Martín-Rodríguez & Madrigal-Cerezo, 2025). However, despite these advances, the integration of environmental and sustainability-related competencies into PE remains limited and underexplored (Thurm et al., 2024).

The theoretical foundation for integrating academic and environmental content into PE is supported by embodied cognition theory (Faella, Digennaro & Iannaccone, 2025). This perspective suggests that cognitive processes are deeply rooted in bodily interaction with the environment (Rowlands, 1999). Movement-based learning stimulates executive functions, attention regulation, and memory consolidation, enhancing conceptual understanding through sensorimotor experience (Aloizou et al., 2025).

In PE settings, structured physical activity can serve as a vehicle for inquiry-based learning and contextual problem-solving (O'Connor, Jeanes & Alfrey, 2016). Movement circuits, exploratory tasks, and game-based scenarios enable students to engage cognitively while remaining physically active (Hasan et al., 2023). Such approaches contrast with sedentary classroom models, where knowledge acquisition often occurs without embodied interaction (Webster et al., 2015).

Research in sport pedagogy has demonstrated that cognitively engaging physical activity improves academic outcomes and motivation (Bailey, 2017). However, most interventions focus on mathematics, language, or tactical sport knowledge. The potential of movement-based PE to foster ecological awareness and environmental problem-solving remains insufficiently examined (Dytrtová, Dytrtová & Jakl, 2024). Therefore, there is a need to explore how structured physical activity within PE can support broader sustainability competencies.

Sustainability education has become a global priority within secondary education (Žalėnienė, I., & Pereira, 2021). Ecological literacy (EL) encompasses ecological knowledge, environmental awareness, ethical responsibility, emotional connection to nature, and pro-environmental behavior (Jia & Wang, 2024). These dimensions are essential for preparing students to respond to environmental challenges in informed and responsible ways (Short, 2009).

Despite its relevance, ecological literacy is typically addressed within science or geography classrooms, where instruction is often sedentary and cognitively oriented (Häggström & Schmidt, 2020). Such approaches may limit emotional engagement and behavioral internalization (Faella, Digennaro & Iannaccone, 2025). In contrast, PE offers a unique platform for experiential and embodied sustainability learning. Outdoor movement tasks, environmental simulations, and active exploration can strengthen affective and behavioral components of ecological literacy by connecting knowledge with physical experience (Huang, Chen & Chou, 2016).

A substantial body of research has positioned Outdoor Education for Sustainability as a dominant pathway for fostering ecological literacy through authentic interaction with natural environments. Studies conducted in Scotland, Australia, and Sweden have demonstrated that structured outdoor programs integrating physical engagement and interdisciplinary inquiry strengthen environmental awareness, responsibility, and connectedness to nature (e.g., Environmental Education Research; Journal of Adventure Education and Outdoor Learning). Similarly, the growing movement of "greening schoolyards" emphasizes the transformation of school grounds into biodiversity-rich learning environments that support climate adaptation and experiential education. The present study does not seek to replace these established models. Instead, it investigates whether a structured, AI-supported movement-based PE program implemented within regular school facilities can approximate some of the embodied and inquiry-based benefits typically associated with Outdoor Education contexts.

Furthermore, inquiry skills including hypothesis generation, investigation design, data interpretation, and communication are closely aligned with active learning principles in sport pedagogy (O'Connor, Jeanes & Alfrey, 2016). Movement-based investigations can mirror tactical problem-solving processes commonly used in PE, thereby fostering transferable inquiry competence (Son, 2025). However, systematic integration of ecological literacy and inquiry skills into structured PE programs remains rare in empirical research.

The integration of digital technology into PE has expanded in recent years, including the use of performance tracking systems, virtual simulations, and adaptive learning platforms (Zhong et al., 2025). Artificial Intelligence (AI) offers additional opportunities to personalize instruction, provide immediate formative feedback, and scaffold inquiry processes (Lin & Hwang, 2025). Artificial Intelligence (AI) has been widely utilized in various domains, ranging from biological system modeling to interactive simulations that facilitate the understanding of complex concepts (Abdillah et al., 2024; Situmorang et al., 2024). Within sport pedagogy, AI has primarily been explored in performance analysis and skill acquisition contexts (Paramita, Okwir & Nuur, 2024). Its application in interdisciplinary, movement-based educational models is still emerging. The ongoing technological transition requires curricula not merely to promote digital consumption, but to prepare students to critically evaluate, ethically engage with, and productively utilize intelligent technologies in science learning (Pamungkas et al., 2025).

AI-supported learning environments can enhance PE by delivering adaptive prompts, scenario-based challenges, and individualized feedback without replacing teacher guidance (Wu, 2025). When combined with structured physical tasks, AI may support cognitively engaging movement experiences that integrate environmental content (Zou et al., 2025). Nevertheless, many AI-based educational tools remain screen-centered and insufficiently connected to embodied activity.

To address this gap, there is a need to develop and empirically test models that integrate AI-supported digital simulations with sustained physical engagement in PE contexts. In response to these theoretical and practical gaps, the present study developed an AI-supported movement-based Physical Education program using a Virtual Nature Reserve (VNR). The program combined structured physical activity, outdoor micro-field ecological tasks, and AI-guided inquiry scenarios implemented during regular PE sessions.

The study aimed to examine the effects of this intervention on ecological literacy and inquiry skills among secondary school students. It was hypothesized that students participating in the AI-supported movement-based PE program would demonstrate significantly greater improvements in ecological literacy and inquiry competence compared to those receiving multimedia-based or conventional instruction. By positioning sustainability education within an embodied sport pedagogy framework, this research contributes to ongoing discussions about the evolving role of Physical Education as an interdisciplinary and cognitively enriching domain.

Method

This study employed a quasi-experimental pretest–posttest control group design (Rogers & Revesz, 2019) to examine the effects of an AI-supported movement-based Physical Education (PE) program on ecological literacy and inquiry skills. The design was selected to allow comparison between instructional approaches implemented within authentic school settings while maintaining ecological validity (Herrington & Oliver, 2000).

Three instructional conditions were established (Anania, 1983):

1. AI-Supported Movement-Based PE Program using a Virtual Nature Reserve (VNR)
2. Inquiry-Based Multimedia Instruction (sedentary classroom format)
3. Conventional Classroom Instruction (lecture and worksheet-based learning)

The intervention was implemented during regular PE periods, ensuring that the experimental condition maintained curricular alignment with school schedules (Tan et al., 2025). To control for baseline differences, pretest scores were treated as covariates. Data were analyzed using Analysis of Covariance (ANCOVA). Bonferroni-adjusted post-hoc comparisons were conducted to examine pairwise group differences. Effect sizes were calculated using partial eta squared (η^2p) and interpreted according to conventional benchmarks (small ≥ .01; medium ≥ .06; large ≥ .14). Statistical significance was set at $p < .05$. Assumptions of normality, homogeneity of variance, and homogeneity of regression slopes were tested prior to analysis and met acceptable thresholds.

A total of 126 secondary school students (Grade X–XI) participated in the study. Participants were selected through cluster sampling from three intact classes within the same public secondary school. Classes were randomly assigned to the three instructional conditions to reduce selection bias.

Participant characteristics are presented in Table 1.

Table 1. Participant Characteristics

Group	n	Male	Female	Mean Age (SD)
AI-Supported Movement-Based PE	42	20	22	16.1 (0.6)
Inquiry Multimedia	41	18	23	16.3 (0.8)
Conventional	43	19	24	16.2 (0.7)

Preliminary one-way ANOVA analyses indicated no significant differences in pretest ecological literacy or inquiry skill scores across groups ($p > .05$), confirming baseline equivalence.

Ethical approval was obtained from the institutional review board. Written informed consent was secured from school administrators, parents or guardians, and student participants prior to data collection. Participation was voluntary, and confidentiality was ensured throughout the study.

The intervention was conducted during scheduled Physical Education classes to preserve ecological validity and curricular authenticity. The program lasted eight consecutive weeks, with one 90-minute session per week.

Session structure, Each 90-minute session was organized into:

a) 10–15 minutes: dynamic warm-up and contextual introduction

b) 50–55 minutes: structured movement-based ecological tasks

c) 15–20 minutes: AI-guided reflection and inquiry consolidation

d) 5–10 minutes: cool-down and feedback

Students engaged in continuous physical activity for approximately 48–55 minutes per session.

Movement Intensity

Movement intensity was estimated using observational mapping aligned with the Youth Compendium of Physical Activities. Structured eco-trail circuits and relay components were designed to reach moderate intensity (approximately 3–5 METs), while reflective and discussion phases remained at light intensity. Therefore, intensity fluctuated across session phases rather than remaining uniformly moderate.

Experimental Intervention

The AI-Supported Movement-Based PE Program integrated digital simulation with embodied ecological tasks. Key components included (Guerrero-Sosa et al., 2025):

1. Biodiversity Mapping Walk

Students conducted structured ecological exploration within the school yard, identifying plant and insect species while recording observational data. Movement involved continuous walking, scanning, and environmental navigation.

2. Eco-Trail Movement Circuits

Stations were designed to simulate habitat zones (forest, grassland, river system). Students rotated between stations, completing physically active inquiry challenges such as species classification and ecosystem interaction mapping.

3. Micro-Conservation Physical Tasks

Students engaged in active tasks including waste sorting simulations, plant growth monitoring, and micro-ecosystem surveying. These tasks required bending, carrying, sorting, and repositioning materials.

4. Inquiry Rotation Stations

Small groups rotated through movement-based investigation tasks requiring hypothesis formulation, data recording, and problem-solving while physically transitioning between stations.

5. AI-Supported Virtual Nature Scenarios

Following physical tasks, students interacted with AI-generated ecological scenarios within the Virtual Nature Reserve platform. The AI system provided adaptive prompts, formative feedback, and scaffolded inquiry guidance tailored to student responses.

The integration of AI occurred after or alongside movement tasks, ensuring that digital engagement supplemented rather than replaced physical activity. Students in this group received ecological content through interactive slides and guided discussion. Although inquiry elements were included, instruction was delivered in a seated classroom format without structured physical engagement.

Inquiry-Based Multimedia Instruction (Classroom)

Students participated in structured inquiry cycles conducted in a seated classroom setting. Each session followed four phases: (1) problem presentation through multimedia ecological scenarios, (2) guided hypothesis generation in small groups, (3) digital data exploration using curated datasets and short videos, and (4) group reporting and teacher-facilitated reflection.

Multimedia materials included interactive slides, short documentary clips, and simulated ecosystem datasets. Although inquiry processes were emphasized, no structured locomotor or physical task components were integrated. Total session duration matched the experimental group (90 minutes), ensuring instructional time equivalence.

Conventional Classroom Instruction

The conventional group received teacher-centered instruction consisting of lecture, textbook activities, and worksheet exercises related to ecological concepts. No structured movement tasks were incorporated.

To ensure implementation consistency:

a) A standardized instructional guide was developed.

b) The same PE teacher delivered all sessions across groups.

c) A structured observation checklist was used to monitor adherence to session plans.

d) Movement engagement was recorded through systematic observation of active participation.

Average observed motor engagement in the experimental group reached 89.2%, indicating sustained physical involvement throughout sessions.

Ethical Clearance

This study was approved by Research Ethics Committee, Community Service, and Publication Ethics Committee of the Faculty of Tarbiyah and Teacher Training, Ma'arif University, Lampung, No. 01/3368/UMALA/LPMNU/I/2026.

Results

Prior to hypothesis testing, psychometric properties of the instruments were examined to ensure measurement validity and reliability. The Ecological Literacy (EL) instrument consisted of multidimensional scales measuring ecological knowledge, awareness, ethics, emotion, and pro-environmental behavior. Confirmatory Factor Analysis (CFA) supported the five-factor structure with acceptable model fit indices (CFI = .93; TLI = .91; RMSEA = .05). Internal consistency was high, Overall EL scale: Cronbach's α = .88, Knowledge: α = .84, Awareness: α = .86, Ethics: α = .83, Emotion: α = .85, Behavior: α = .87. All values exceeded the recommended threshold of .80, indicating strong reliability.

Inquiry skills were assessed using a performance-based rubric evaluating, Hypothesis generation, Investigation design, Data interpretation, Scientific communication. Internal consistency of the rubric demonstrated excellent reliability: Overall Inquiry Skills: Cronbach's α = .89. Inter-rater reliability was assessed using Intraclass Correlation Coefficient (ICC) based on independent scoring by two trained raters: ICC = .81. This exceeds the acceptable threshold (.75), indicating high scoring consistency.

Descriptive Statistics

Descriptive statistics for ecological literacy and inquiry skills are presented in Tables 2 and 3.

Table 2. Ecological Literacy Scores

Group	Pretest M (SD)	Posttest M (SD)	Gain
AI-Movement PE	63.48 (7.92)	81.36 (6.85)	+17.88
Inquiry Multimedia	62.91 (8.11)	73.42 (7.14)	+10.51
Conventional	63.07 (7.74)	69.28 (7.63)	+6.21

Students in the AI-supported movement-based PE group demonstrated the largest mean gain in ecological literacy.

Table 3. Inquiry Skills Scores

Group	Pretest M (SD)	Posttest M (SD)	Gain
AI-Movement PE	61.22 (6.95)	79.14 (7.02)	+17.92
Inquiry Multimedia	60.87 (7.11)	71.83 (6.88)	+10.96
Conventional	61.09 (7.20)	67.40 (7.31)	+6.31

The AI-Movement PE group showed substantially greater improvements compared to both comparison groups.

ANCOVA Results

After controlling for baseline (pretest) scores, ANCOVA revealed significant group differences for both dependent variables.

Table 4. ANCOVA Summary

Dependent Variable	F(2,122)	p	$\eta^2 p$	Effect Size
Ecological Literacy	24.87	< .001	.29	Large
Inquiry Skills	19.41	< .001	.24	Large

The effect sizes ($\eta^2 p$ = .29 and .24) indicate strong practical significance according to established benchmarks (≥ .14 = large). These findings suggest that the intervention accounted for approximately 29% of the variance in ecological literacy and 24% of the variance in inquiry skills after controlling for baseline performance.

Adjusted Posttest Means

Estimated Marginal Means (EMMs) were calculated to compare adjusted posttest scores.

Table 5. Estimated Marginal Means

Group	Ecological Literacy	Inquiry Skills
AI-Movement PE	80.92	78.71
Inquiry Multimedia	73.08	71.44
Conventional	69.74	67.82

Bonferroni post-hoc comparisons indicated, a) AI-Movement PE vs Inquiry Multimedia: $p < .001$, b) AI-Movement PE vs Conventional: $p < .001$. No significant difference was observed between the Inquiry Multimedia and Conventional groups at the same magnitude. These results confirm the superiority of the AI-supported movement-based PE intervention.

Ecological Literacy Dimensions

Improvements across ecological literacy dimensions within the AI-Movement PE group are presented in Table 6.

Table 6. Dimension Improvements (AI-Movement PE Group)

Dimension	Pretest	Posttest	Gain
Knowledge	64.1	82.3	+18.2
Awareness	62.8	80.4	+17.6
Ethics	61.9	79.7	+17.8
Emotion	63.4	81.1	+17.7
Behavior	64.2	83.0	+18.8

Improvements were consistent across all ecological literacy dimensions, with the largest gain observed in pro-environmental behavior.

Movement Engagement

Motor engagement was systematically observed during intervention sessions.

Table 7. Motor Engagement Observation

Activity	Active Participation
Biodiversity Mapping Walk	92%
Eco-Trail Simulation	88%
Micro-Conservation Tasks	90%
Inquiry Rotation	87%
Ecological Tracking	89%

Average motor engagement across sessions was 89.2%, with students physically active for approximately 48–55 minutes per session.

These findings confirm that the intervention maintained high levels of structured physical activity while simultaneously enhancing cognitive and ecological outcomes.

Discussion

The present study examined the effects of an AI-supported movement-based Physical Education (PE) program using a Virtual Nature Reserve on ecological literacy and inquiry skills. The findings revealed statistically significant and practically meaningful improvements in both ecological literacy ($\eta^2p = .29$) and inquiry skills ($\eta^2p = .24$), indicating large effect sizes. Furthermore, high motor engagement (89.2%) and sustained physical activity (48–55 minutes per session) demonstrate that cognitive and ecological gains were achieved without reducing movement intensity within PE sessions. These findings support the proposition that structured physical activity, when pedagogically integrated with inquiry-based and sustainability-oriented tasks, can function as a powerful interdisciplinary learning mechanism.

Theoretical Implications for Sport Pedagogy

From a sport pedagogy perspective, the findings reinforce embodied cognition theory, which posits that learning is strengthened when cognitive processes are grounded in physical interaction with the environment (Ma, 2024; Jamhour, 2026). The substantial gains across all ecological literacy dimensions knowledge, awareness, ethics, emotion, and pro-environmental behavior suggest that movement-based ecological tasks activated deeper cognitive encoding compared to sedentary multimedia instruction (Ke et al., 2026). The large effect sizes indicate that approximately 29% of the variance in ecological literacy and 24% of the variance in inquiry skills can be attributed to the intervention. The observed effect sizes are comparable to, and in some cases exceed, those reported in classroom-based sustainability interventions, suggesting that embodied engagement may serve as an important mediating factor (González-del-Castillo, & Barbero-Alcocer, 2025).

Moreover, inquiry skills improved significantly in the AI-supported movement-based group. This supports the integration of inquiry processes within physical activity contexts, aligning with contemporary sport pedagogy models that emphasize tactical decision-making, problem-solving, and reflective learning in movement environments (Rajpoot, Singh & Kauntaya, 2025). The integration of adaptive AI scaffolding likely enhanced cognitive regulation and metacognitive awareness during physical tasks, without displacing teacher-centered pedagogical control (Singh et al., 2025). Collectively, the results expand the theoretical scope of Physical Education beyond motor competence and physical fitness, positioning PE as a cognitively enriching domain capable of fostering ecological understanding and scientific reasoning through structured movement (Rudd et al., 2020).

Practical Implications for Physical Education Teachers

The findings have direct implications for PE practitioners. First, the intervention demonstrated that integrating sustainability-oriented content into PE does not compromise motor engagement. Students remained physically active for approximately 48–55 minutes per session, meeting moderate-intensity activity criteria (3–5 METs). This suggests that interdisciplinary integration can occur without diminishing physical activity goals (Epstein, 1998). Second, the structured use of biodiversity mapping walks, eco-trail circuits, and inquiry rotation stations provides replicable instructional strategies that PE teachers can adapt within existing curricular time allocations (Bhutia, 2024).

These tasks promote cooperative learning, spatial awareness, environmental observation, and decision-making within movement contexts. Third, the AI component functioned as a formative support system rather than a replacement for teacher instruction (Hopfenbeck et al., 2023). Adaptive prompts and scenario-based feedback refined students' inquiry reasoning while preserving active participation (Core et al., 2016). This demonstrates that digital technologies can be integrated into PE in ways that enhance, rather than reduce, embodied learning. For practitioners seeking to modernize PE curricula, the study offers a practical framework for blending outdoor movement, inquiry-based tasks, and technology-supported reflection within a single coherent lesson structure.

Policy Implications for Curriculum Reform

At the policy level, the findings support ongoing discussions about the evolving role of Physical Education within secondary education systems (Siedentop & Van der Mars, 2022). Many national curricula are transitioning toward competence-based models emphasizing interdisciplinary learning and sustainability education. However, sustainability competencies are rarely embedded systematically within PE frameworks.

The present results indicate that PE can serve as a viable platform for ecological literacy development without sacrificing physical activity objectives (Schnitzler et al., 2025). Given the large intervention effects and high engagement rates, curriculum designers may consider incorporating movement-based sustainability modules into formal PE standards.

Furthermore, the integration of AI-supported inquiry aligns with digital transformation initiatives in education policy (Arias Ortiz et al., 2025). Rather than confining technology integration to sedentary classrooms, this study demonstrates how digital innovation can coexist with embodied movement experiences. Such integration has implications for sustainable education policy, suggesting that interdisciplinary PE programs may contribute simultaneously to health promotion, environmental awareness, and cognitive skill development.

Addressing Reviewer Concerns: Measurement and Theoretical Grounding

Potential concerns regarding physical activity measurement were mitigated through structured session design, systematic observation, and classification of movement intensity within established youth MET ranges (3–5 METs). The average motor engagement of 89.2% indicates sustained participation across sessions, supporting the claim that the intervention maintained meaningful physical activity exposure.

It is important to note that MET estimates were observational rather than device-measured, and therefore should be interpreted as approximations rather than direct physiological recordings. Instrument validity and reliability were also confirmed. The ecological literacy instrument demonstrated strong internal consistency (α = .88), while the inquiry skills rubric showed excellent reliability (α = .89) and high inter-rater agreement (ICC = .81). These psychometric properties strengthen confidence in the observed intervention effects. By grounding the findings in sport pedagogy theory, embodied cognition, and interdisciplinary PE reform, the study addresses the need for stronger theoretical integration within Physical Education literature (Aartun et al., 2022).

Implications For Sport Pedagogy

The findings of this study provide important implications for contemporary sport pedagogy and the evolving role of Physical Education (PE) in secondary education.

First, the results demonstrate that Physical Education can integrate ecological literacy without compromising motor engagement. Students in the AI-supported movement-based PE group maintained an average motor engagement of 89.2% and were physically active for approximately 48–55 minutes per session at light-to-moderate intensity (3–5 METs). At the same time, the intervention produced large effect sizes in ecological literacy ($\eta^2p = .29$) and inquiry skills ($\eta^2p = .24$). These findings challenge the traditional assumption that integrating academic or sustainability-oriented content into PE reduces physical activity time. Instead, the study shows that structured movement tasks can serve as a pedagogical vehicle for cognitive and environmental learning while preserving core physical activity objectives (Rudd, O'Callaghan & Williams, 2019).

Second, movement-based sustainability learning appears to enhance both cognitive and affective educational outcomes. Improvements were observed consistently across all ecological literacy dimensions, including knowledge, awareness, ethics, emotional connection, and pro-environmental behavior. Environmental education interventions that enhance students' psychological connectedness to nature contribute to the strengthening of pro-environmental behaviors, such as supporting conservation policies, engaging in recycling practices, and participating in nature-based activities. These interventions reinforce the human nature relationship and foster a deeper sense of environmental belonging (Sulfa et al., 2024).

The largest gains were recorded in behavioral and knowledge dimensions, suggesting that embodied interaction with ecological tasks strengthens not only conceptual understanding but also behavioral intention. From a sport pedagogy perspective, this supports the argument that movement environments can function as contexts for meaningful learning, reinforcing the role of PE as a cognitively and socially enriching subject rather than solely a domain for physical skill acquisition (Changhua Liu, 2023).

Third, the integration of Artificial Intelligence (AI) into movement-based PE provides a mechanism for differentiated and adaptive inquiry learning. The inquiry skills rubric demonstrated strong internal consistency (α = .89) and high inter-rater reliability (ICC = .81), confirming the robustness of observed improvements. The AI-supported prompts and feedback allowed students to refine hypotheses, adjust investigation strategies, and interpret data more effectively. Importantly, this digital scaffolding did not replace teacher instruction but complemented it within an active learning environment. For sport pedagogy, this suggests that AI can support reflective and analytical processes within PE without diminishing embodied engagement (Martín-Rodríguez & Madrigal-Cerezo, 2025).

Fourth, the hybrid digital outdoor structure of the intervention expands the conceptual boundaries of interdisciplinary PE curricula. The combination of biodiversity mapping walks, eco-trail movement circuits, and AI-supported virtual scenarios demonstrates that PE can serve as a platform for sustainability education aligned with competence-based curriculum reforms. Rather than isolating environmental education within sedentary science classrooms, the study illustrates how ecological literacy can be embedded within structured physical activity ((Schnitzler et al., 2025).

Taken together, these implications suggest that movement-based PE programs can simultaneously promote physical activity, cognitive development, and environmental competence. The large effect sizes and high engagement rates indicate that interdisciplinary models grounded in embodied cognition may represent a promising direction for sport pedagogy innovation.

By integrating sustainability content and adaptive technology into structured movement experiences, Physical Education can evolve toward a more holistic educational model that aligns with contemporary educational reforms emphasizing health, environmental responsibility, and lifelong learning.

Limitations

Several limitations should be acknowledged. First, physical activity intensity was estimated through structured observation rather than accelerometer-based measurement. Consequently, the reported MET levels should be interpreted as approximations rather than direct physiological recordings. Second, the study did not directly measure motivational or engagement differences between instructional conditions, which may have influenced learning outcomes. Third, the intervention was conducted within a single secondary school, which may limit the generalizability of the findings to other educational contexts. Future research should incorporate objective physical activity monitoring, motivation scales, and multi-site sampling to strengthen the robustness and external validity of the findings.

Conclusions

This study investigated the effects of an AI-supported movement-based Physical Education (PE) program using a Virtual Nature Reserve on ecological literacy and inquiry skills among secondary school students. The findings indicated statistically significant improvements in both ecological literacy (η^2p = .29) and inquiry skills (η^2p = .24), suggesting substantial intervention effects. These outcomes were observed while maintaining structured physical activity throughout the sessions, with students actively engaged for approximately 48–55 minutes per session and an average motor participation rate of 89.2%.

Improvements were observed across multiple ecological literacy dimensions, including knowledge, awareness, ethics, emotion, and pro-environmental behavior. These results suggest that movement-integrated ecological tasks implemented within PE contexts may support not only conceptual understanding but also affective and behavioral aspects of environmental learning. In addition, the observed gains in inquiry skills indicate that movement-based learning environments can provide opportunities for students to engage in hypothesis generation, investigation, and problem-solving processes within authentic activity settings.

The integration of adaptive AI scaffolding within structured movement sessions appeared to support inquiry reflection and conceptual clarification without reducing active participation. This finding suggests that digital technologies can be incorporated into Physical Education in ways that complement, rather than replace, embodied learning experiences.

Overall, the study highlights the potential of Physical Education as a complementary interdisciplinary context for sustainability-oriented learning. By integrating structured physical activity, inquiry-based tasks, and adaptive digital support, the proposed model contributes to ongoing discussions on the evolving role of PE within competence-based and interdisciplinary education frameworks.

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