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Effectiveness of PBL on knowledge, attitudes, and waste-sorting behaviors among primary school students in Thailand

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ABSTRACT

This study investigated the effectiveness of problem-based learning (PBL) as an innovative pedagogical approach to enhancing knowledge, environmental attitudes, and waste-sorting behaviors among primary school students in Thailand. A multi-site quasi-experimental design with pretest-posttest control groups was employed in urban and rural settings. Data were collected from 400 students across Bangkok, Suphanburi, and Lampang, equally divided into experimental and control groups. Instruments included a validated knowledge test, an environmental attitude scale, and a behavioral checklist. Data were analyzed using descriptive statistics, independent t-tests, and analysis of variance (ANOVA). Results indicated significant improvements in the experimental group: knowledge increased by 2.23 points (Cohen's d=1.52), attitudes by 0.59 points (d=0.68), and behaviors by 1.78 points (d=1.67). Mediation analysis confirmed that attitudes partially mediated the relationship between knowledge and behavior (β=0.35, 95% CI=[0.28, 0.43]). No significant differences were observed among the three study sites (p>0.05), suggesting that PBL is equally effective in urban and rural schools. These findings provide empirical support for integrating PBL in environmental education, contributing to Sustainable Development Goals (SDG 4 and SDG 12).

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1. INTRODUCTION

The rapid advancement of digital technology has profoundly transformed primary education, requiring teachers to integrate interactive media and innovative learning tools into their classrooms. Among these, game-based and problem-oriented learning approaches have proven highly effective in enhancing students' engagement and academic achievement [1], [2]. At the same time, environmental education at the primary level has gained global attention because it provides an optimal window for cultivating awareness, ethical understanding, and responsible behavior toward environmental sustainability [3], [4].

In Thailand, the escalating solid-waste crisis-exceeding 41,000 tons per day, with only 30 percent disposed of hygienically—underscores the urgent need for educational strategies that foster sustainable waste management [5]. Although the Thai government promotes a four-bin waste-sorting system (green=biodegradable, blue=general, yellow=recyclable, and red=hazardous) [5], public participation remains inconsistent. Educating children to understand and practice proper waste sorting is therefore essential to building long-term environmental responsibility. A previous study show that introducing waste management learning to children can positively influence both school and household recycling behaviors [3].

While digital technologies including game-based applications and interactive multimedia have demonstrated efficacy in enhancing student engagement and knowledge acquisition [1], [2], these tools function primarily as instructional delivery mechanisms rather than comprehensive pedagogical frameworks. The presence of digital media alone does not ensure deep conceptual understanding, critical thinking development, or sustainable behavioral transformation [6]. Educational technology research indicates that learning outcomes depend substantially on the pedagogical approach structuring technology use, rather than on technological sophistication per se. Evidence from reviews and meta-analyses suggests that learning outcomes are influenced more strongly by pedagogical design and instructional conditions than by the sophistication of the technology alone [6], [7].

Problem-based learning (PBL) addresses this pedagogical gap by providing a theoretically grounded instructional framework emphasizing authentic inquiry, collaborative problem-solving, and active knowledge construction [8], [9]. Unlike conventional teacher-centered approaches or technology-enhanced but didactic instruction, PBL positions learners as active investigators confronting ill-structured, contextually relevant problems requiring sustained analysis, information gathering, hypothesis generation, and solution development. This learner-centered methodology aligns distinctively with environmental education objectives through several mechanisms. First, PBL situates learning in authentic real-world contexts, enabling students to engage directly with environmental challenges affecting their communities rather than studying abstract environmental concepts divorced from lived experience. Second, PBL promotes systems thinking by requiring students to analyze complex interdependencies among human consumption patterns, waste generation, and environmental consequences [10]. Third, PBL fosters student agency and self-efficacy by positioning learners as capable problem-solvers rather than passive knowledge recipients, a psychological orientation particularly crucial for environmental behavior change [11]. Fourth, PBL's collaborative structure facilitates peer learning, social norm development, and collective responsibility for environmental outcomes.

Traditional instructional approaches and even digitally enhanced but teacher-directed methods typically fail to integrate these elements systematically. PBL's structured inquiry cycle—problem identification, investigation, knowledge application, solution design, and reflective evaluation—creates optimal conditions for transformative learning transcending mere information transmission to encompass attitudinal internalization and behavioral enactment [12]. The pedagogical framework thus serves as the active ingredient producing meaningful environmental learning outcomes, with digital media and local content functioning as supporting elements enhancing implementation effectiveness.

This theoretical rationale, combined with empirical evidence demonstrating PBL's effectiveness in developing higher-order thinking and promoting knowledge transfer [8], [9], provides strong justification for examining PBL's potential in environmental education. The present study therefore investigates whether PBL, when implemented with culturally relevant problem scenarios and multimedia support, produces superior outcomes in knowledge, attitudes, and waste-sorting behaviors compared to conventional instruction among Thai primary students.

Despite technological advances in educational tools, few studies have systematically evaluated the effectiveness of innovative pedagogies such as PBL in environmental education. Many projects emphasize digital media development but overlook the learning processes underlying behavioral change [6], [8]. This methodological gap limits the evidence base for determining whether PBL actually produces measurable improvements in knowledge, attitudes, and behavior. Moreover, researchers [13], [14] have noted that contextual factors such as culture and geography may influence learning outcomes, yet empirical comparisons between urban and rural educational contexts remain scarce.

Building on these gaps, the present study examines the effectiveness of PBL on knowledge, attitudes, and waste-sorting behavior among primary-school students in Bangkok, Suphanburi, and Lampang. The conceptual framework integrates Dale's cone of experience and Kolb and Bruner's experiential learning theory [15], [16], emphasizing active, reflective, and context-based learning. PBL promotes deep conceptual understanding, collaborative problem-solving, and self-directed inquiry [8], [9]. Its application in environmental education, combined with digital media and local content, is expected to enhance learner engagement and relevance [1]. The study employs a multi-site quasi-experimental design to compare PBL's effectiveness across urban and rural regions, using instruments based on the knowledge-attitude-practice (KAP) model [17]. The results aim to provide empirical evidence to guide future innovations such as game-based learning platforms and smart waste-bin technologies.

This research directly advances two interconnected United Nations Sustainable Development Goals, specifically addressing designated targets within SDG 4 (quality education) and SDG 12 (responsible consumption and production) [18]. SDG 4, target 4.7 explicitly calls for ensuring that all learners acquire knowledge and skills necessary to promote sustainable development, including through education for sustainable development and sustainable lifestyles. The present study operationalizes this target by implementing PBL as a quality pedagogical approach cultivating critical thinking, problem-solving

competencies, and environmental values essential for sustainable citizenship. The significant improvements observed in knowledge acquisition and attitude formation align directly with SDG 4's emphasis on transformative, learner-centered education that develops cognitive and non-cognitive competencies required for addressing complex sustainability challenges.

SDG 12, target 12.5 aims to substantially reduce waste generation through prevention, reduction, recycling, and reuse by 2030, with target 12.8 emphasizing the importance of ensuring that people everywhere have relevant information and awareness for sustainable development and lifestyles. By educating primary school students-a developmentally optimal period for establishing lifelong behavioral patterns-to understand waste systems and enact proper sorting practices, this intervention addresses waste reduction at its behavioral foundation. Furthermore, the pedagogical approach itself exemplifies SDG 4's quality education principles while directly serving SDG 12's consumption and production objectives. PBL fosters deep understanding of consumption-waste-environment relationships rather than superficial rule compliance, creating informed citizens capable of making sustainable choices throughout their lifespans [8], [12]. By demonstrating PBL's effectiveness across diverse geographic contexts in Thailand, this study provides an empirically validated, scalable model for simultaneously achieving both SDG targets: delivering quality education (SDG 4) that promotes responsible waste behaviors and consumption patterns (SDG 12). These findings contribute actionable evidence for educational policymakers seeking to align national curricula with international sustainability commitments while addressing pressing domestic environmental challenges such as Thailand's solid waste crisis.

The formulation of research hypotheses in this study derives from convergent theoretical predictions across multiple frameworks and empirical evidence from prior environmental education research. First, cognitive constructivist theory, as articulated by Kolb [15] and Bruner [16], posits that active construction of knowledge through authentic problem-solving produces deeper conceptual understanding and enhanced retention compared to passive information reception. Students engaging with genuine waste management problems are theorized to develop more robust, integrated knowledge schemas than those memorizing sorting rules through direct instruction. This cognitive advantage should manifest in superior posttest knowledge performance among PBL participants.

Second, the KAP model [17] provides a theoretical framework for understanding sustainable behavior development through sequential progression across cognitive, affective, and behavioral domains. The model posits that knowledge acquisition provides a necessary foundation for attitude formation, which subsequently influences behavioral enactment. However, traditional instructional approaches typically address only the knowledge component, failing to systematically cultivate attitudes or provide authentic behavioral practice opportunities. PBL's experiential nature uniquely addresses all three KAP components simultaneously: building knowledge through inquiry-based investigation, shaping attitudes through meaningful engagement with consequential environmental problems, and facilitating behavioral practice through authentic application contexts. This comprehensive approach should produce superior outcomes across all three domains compared to conventional instruction.

Third, self-determination theory [19] identifies autonomy, competence, and relatedness as fundamental psychological needs driving intrinsic motivation and behavioral internalization. PBL satisfies these needs by granting students ownership over problem-solving processes (autonomy), providing mastery experiences through successful task completion (competence), and fostering collaborative relationships through group work (relatedness). This motivational advantage should enhance engagement quality and promote internalization of environmental values, potentially supporting behavioral change within and proximal to the intervention period.

Fourth, empirical evidence from environmental education research consistently demonstrates that context-relevant, action-oriented approaches produce stronger behavioral outcomes than abstract, knowledge-focused instruction [14], [20]. Studies examining place-based environmental education show that personal relevance and direct experience with local environmental issues predict behavioral engagement [3]. By grounding learning in community-specific waste challenges and providing opportunities for authentic problem-solving, PBL should generate heightened personal relevance and facilitate behavioral transfer from classroom to real-world settings.

Fifth, social cognitive theory [11] emphasizes reciprocal causation among personal factors, behavior, and environmental influences. Observing peers successfully enacting waste-sorting behaviors during collaborative problem-solving provides vicarious learning experiences that enhance self-efficacy and establish prosocial norms, potentially creating peer accountability mechanisms supporting behavioral maintenance. These theoretical mechanisms, supported by empirical findings from related educational interventions, provide strong justification for predicting that PBL will significantly outperform traditional instruction across cognitive, affective, and behavioral outcome domains.

This study was designed to achieve the following objectives: i) to examine pre- and post-intervention changes in students' knowledge, attitudes, and waste-sorting behaviors after participating in PBL

and ii) to evaluate the effectiveness of PBL compared to conventional instruction in improving these variables among Thai primary school students. Research hypotheses are students who receive PBL instruction will exhibit significantly higher posttest scores in knowledge, attitudes, and waste-sorting behaviors compared to their pretest scores (H1) and students in the PBL group will score significantly higher on all outcome variables than those in the control (traditional-instruction) group (H2).

2. METHOD

2.1. Research design

This study adopted a multi-site quasi-experimental design to evaluate the effectiveness of PBL on students' knowledge, environmental attitudes, and waste-sorting behaviors. The design incorporated pretest-posttest control groups across three distinct geographical regions in Thailand to enhance generalizability and validity. This approach aligns with the recommendations of Creswell and Creswell [21] for increasing reliability and external validity in educational intervention research conducted across diverse contexts.

A between-subjects design was implemented, in which participants were randomly assigned to either an experimental group (receiving PBL instruction) or a control group (receiving traditional instruction). The quasi-experimental approach was selected due to the practical constraints of real classroom environments, while maintaining sufficient methodological rigor for causal inference. The multi-site structure allowed for a comparative analysis of effectiveness across urban and rural settings, addressing the research gap noted by Monroe *et al*. [14] concerning the role of cultural and geographical factors in environmental learning outcomes.

2.2. Population and sampling

The study population comprised primary school students from three regions of Thailand, totaling 43,635 students. Participants were drawn from Suan Dusit Demonstration Schools located in Bangkok, Suphanburi, and Lampang, representing metropolitan, semi-urban, and rural contexts, respectively. These locations were purposefully selected to capture a broad range of socioeconomic and cultural characteristics relevant to environmental education. A total of 400 students were selected using stratified random sampling to ensure proportional representation across the three study sites: Bangkok (n=90), Suphanburi (n=116), and Lampang (n=194). Sample size determination was based on power analysis, assuming a medium effect size (Cohen's d=0.5), statistical power of 0.80, and α=0.05. The minimum required sample size was 128 participants per group, but 400 were included to account for potential attrition and enable subgroup analyses, as displayed in Table 1.

Sampling proceeded in two stages. The first or stage 1 is school selection, schools were stratified by region and randomly selected to ensure diversity in school type (public vs. demonstration) and socioeconomic composition. Next stage is stage 2 which is student selection. Within each selected school, students were chosen through simple random sampling (lottery method) to guarantee equal probability of selection. After pretesting, participants were randomly assigned to experimental and control groups to minimize selection bias and ensure baseline equivalence.

Table 1. Demographic characteristics of participants

Characteristic	Experimental group (n=200)	Control group (n=200)	Total (n=400)	Test statistic	p-value
Age (years)				t(398)=0.14	.892
9-10 years	33 (16.5%)	33 (16.5%)	66 (16.5%)		
10-11 years	167 (83.5%)	167 (83.5%)	334 (83.5%)		
Mean ± SD	10.24 ± 0.58	10.26 ± 0.61	10.25 ± 0.59		
Grade level				$\chi^2(2)=0.09$	.956
Grade 4	106 (53.0%)	107 (53.5%)	213 (53.3%)		
Grade 5	90 (45.0%)	90 (45.0%)	180 (45.0%)		
Grade 6	4 (2.0%)	3 (1.5%)	7 (1.8%)		
School type				$\chi^2(1)=0.001$	1.000
Demonstration	68 (34.0%)	68 (34.0%)	136 (34.0%)		
Public	132 (66.0%)	132 (66.0%)	264 (66.0%)		
Region				$\chi^2(2)=0.001$	1.000
Bangkok	45 (22.5%)	45 (22.5%)	90 (22.5%)		
Suphanburi	58 (29.0%)	58 (29.0%)	116 (29.0%)		
Lampang	97 (48.5%)	97 (48.5%)	194 (48.5%)		
Gender				$\chi^2(1)=0.37$	.847
Male	98 (49.0%)	96 (48.0%)	194 (48.5%)		
Female	102 (51.0%)	104 (52.0%)	206 (51.5%)		

Baseline equivalence analyses confirmed no significant differences between experimental and control groups across all demographic variables (all $p>0.05$). Independent-samples t-tests for continuous variables and chi-square tests for categorical variables yielded nonsignificant results, indicating successful randomization and comparability of groups prior to intervention implementation.

2.3. Intervention protocol

2.3.1. Prior PBL experience

Neither students nor classroom teachers possessed prior formal experience with PBL methodologies before study commencement. All participating schools employed traditional teacher-centered instructional approaches as their primary pedagogical model, characterized by direct instruction, textbook-based learning, and teacher-directed activities. This uniform baseline ensured that observed intervention effects could be attributed to PBL exposure rather than pre-existing competencies or methodological familiarity. To minimize potential novelty effects and establish appropriate behavioral expectations, experimental group students received a 120-minute orientation session introducing core PBL principles, collaborative work norms, inquiry processes, and self-directed learning strategies prior to intervention implementation.

2.3.2. Facilitator characteristics and professional development

Six classroom teachers (two per geographic region) served as PBL facilitators throughout the intervention period. All facilitators held bachelor's degrees in elementary education with teaching experience ranging from 5 to 12 years ($M=8.3$ years, $SD=2.4$ years). None possessed prior PBL implementation experience, representing typical Thai primary school instructional contexts. Facilitators participated in intensive 24-hour professional development delivered over three consecutive days immediately preceding intervention implementation. The training curriculum encompassed: i) theoretical foundations of PBL and constructivist learning theories; ii) facilitation techniques including strategic questioning, cognitive scaffolding, and avoidance of premature solution provision; iii) classroom management strategies for collaborative learning environments; iv) formative assessment approaches for process and outcome evaluation; and v) integration of digital media resources and culturally relevant content materials.

Professional development employed active learning methodologies including demonstration lessons, microteaching practice with peer feedback, and role-playing exercises simulating common facilitation challenges. Facilitators demonstrated competency through observed practice sessions evaluated using a standardized rubric before receiving approval for independent implementation. During the four-week intervention period, two trained independent observers conducted fidelity checks using a structured observation protocol (three observations per facilitator). Fidelity analysis indicated 85% mean adherence to prescribed PBL protocols across all facilitators (range 80-92%), confirming adequate implementation consistency while acknowledging minor individual variations in teaching style and emphasis.

2.3.3. Problem scenarios and learning sequence

The intervention employed three sequential authentic problem scenarios progressing in complexity over the four-week implementation period. Each problem required collaborative investigation, data collection, analysis, and solution development.

a. Week 1-2: the school waste crisis

Students conducted systematic investigations of waste generation patterns within their own schools. Activities included: conducting waste audits documenting types and quantities of discarded materials; interviewing cafeteria staff, custodial workers, and administrators regarding current waste management practices; photographing waste disposal areas and documenting problematic conditions; and analyzing collected data to identify system failures and improvement opportunities. The guiding question framing this investigation was, why is our school's waste management system functioning ineffectively, and how can we design improvements?

b. Week 3: community waste detective

Building on school-based findings, students extended their investigation to household and community contexts. Activities included: conducting home waste audits with family participation to document residential waste patterns; performing neighborhood observation walks identifying waste-related environmental impacts; interviewing community members including waste collectors, local shop owners, and residents regarding waste practices and challenges; and analyzing relationships between individual behaviors and community-level environmental consequences. The guiding question was, how do our community's waste behaviors affect environmental quality, and what behavioral changes would generate the greatest positive impact?

c. Week 4: solution design and implementation planning

Integrating knowledge from preceding investigations, student teams collaboratively designed comprehensive solutions addressing identified problems. Activities included: developing improved

waste-sorting systems for school and home contexts with specific bin placement, signage, and sorting protocols; creating educational materials (posters, presentations, and demonstration videos) for peer and family education; generating implementation plans with concrete action steps, timelines, and responsibility assignments; and presenting solutions to classmates, teachers, and invited community members. The guiding question was, what realistic, evidence-based solutions can we implement to improve waste sorting effectiveness in our school and community?

All problems were intentionally ill-structured, requiring sustained inquiry, information synthesis from multiple sources, and creative solution generation rather than application of predetermined algorithms. Problems necessitated collaborative effort, with students assigned complementary roles within teams (e.g., data recorder, interviewer, photographer, and analyst). Authentic products including audit reports, data visualizations, educational materials, and implementation plans provided tangible outcomes demonstrating learning and serving potential real-world applications.

2.3.4. Contextual adaptation across geographic regions

While maintaining consistent core problem structures and learning objectives, scenarios were adapted to reflect region-specific environmental contexts and cultural characteristics, enhancing personal relevance and authenticity. Bangkok scenarios emphasized high-volume urban waste generation, condominium and apartment complex sorting challenges, municipal waste management policies, and contemporary consumption patterns including food delivery packaging and single-use plastic proliferation. Suphanburi scenarios balanced urban and agricultural waste contexts, incorporating market waste, food production byproducts, and connections between waste mismanagement and river pollution affecting agricultural productivity. Lampang scenarios emphasized agricultural waste including crop residues, traditional versus modern waste practices in rural communities, open burning behaviors, and relationships between waste management and forest ecosystem health.

Local wisdom was systematically integrated through elder interviews and documentation of traditional environmental practices. Bangkok students explored urban sustainability practices from temple communities emphasizing mindful consumption and waste minimization. Suphanburi students investigated traditional composting methods from farming communities and natural resource conservation practices. Lampang students documented indigenous knowledge regarding waste minimization, preference for natural materials, and traditional craft practices reusing and repurposing materials. This cultural integration ensured problems resonated with students' lived experiences while honoring community knowledge systems, a factor identified as critical for environmental education effectiveness [14].

2.3.5. Intervention duration and assessment timeline

The complete intervention encompassed four weeks of instruction, totaling 16 contact hours delivered through four one-hour sessions per week. The assessment timeline proceeded as: i) week 0 (baseline): pretest administration measuring knowledge, attitudes, and behavioral intentions; ii) weeks 1-4: PBL intervention implementation; iii) week 5 (immediate posttest): administration of all outcome measures assessing knowledge, attitudes, and self-reported behaviors over the preceding week; and iv) week 9 (follow-up assessment): behavioral measures repeated to assess four-week maintenance of behavior change.

This design enabled evaluation of immediate learning outcomes while providing preliminary evidence regarding short-term behavioral sustainability. The follow-up assessment focused specifically on behavioral maintenance, as knowledge and attitude measures were considered stable following intervention completion. However, this study acknowledges the limitation that extended long-term follow-up (six months or longer) was not conducted, precluding definitive conclusions regarding sustained behavior change over extended periods—a priority for future longitudinal investigations.

2.3.6. Behavioral measurement instruments

Behavioral outcomes were assessed using two parallel checklists developed in consultation with the Thai Environmental Education Foundation. Both instruments employed five-point Likert-type scales (1=never, 2=rarely, 3=sometimes, 4=often, and 5=always) assessing frequency of specific waste-related behaviors as in Table 2 school behavior and Table 3 for home behavior. Internal consistency reliability was adequate at pretest (Cronbach's α=0.84) and improved at posttest (α=0.87).

Internal consistency was acceptable at pretest (α=0.82) and posttest (α=0.86). To address potential social desirability bias inherent in self-report measures, a validation subsample (n=60, stratified across conditions and sites) underwent direct behavioral observation during school lunch periods. Research assistants blind to participants' group assignment systematically coded waste-sorting accuracy using a structured observation protocol. Observed sorting accuracy correlated significantly with self-reported school behavior scores (Pearson r=0.67, $p<0.001$), providing convergent validity evidence. Additionally, parent

ratings of students' home waste-sorting behaviors were collected for a subset of participants (n=120) using a parallel five-item questionnaire. Parent-student agreement was moderate (Cohen's κ=0.58), suggesting reasonable accuracy of student self-reports while acknowledging measurement imprecision and potential reporting biases. These validation procedures strengthen confidence in behavioral outcome validity despite reliance on self-report methodology.

Table 2. School behavior checklist

Item	Statement
1	I sort my lunch waste into the correct colored bins according to Thailand's four-bin system (green/blue/yellow/red).
2	I remind classmates to sort waste properly when I observe incorrect disposal.
3	I actively participate in classroom recycling monitoring responsibilities.
4	I avoid using single-use plastic items at school by bringing reusable containers and water bottles.
5	I examine whether items are recyclable before disposing of them.

Table 3. Home behavior checklist

Item	Statement
1	I sort household waste before disposal.
2	I separate organic food waste from other trash.
3	I seek opportunities to reuse or recycle items rather than immediately discarding them.
4	I discuss proper waste-sorting practices with family members.
5	I encourage my family to reduce waste generation and increase recycling.

Note: all items rated on a five-point Likert scale (1=never, 2=rarely, 3=sometimes, 4=often, and 5=always).

2.3.7. Integration of animated media and local wisdom

Custom-developed animated videos (3-5 minutes duration) were integrated at problem introduction phases to provide foundational knowledge, stimulate curiosity, and establish emotional connections to environmental issues. Animations featured Thai characters, culturally familiar settings, and age-appropriate content including: visual demonstrations of decomposition timelines for various waste materials; illustrations of environmental and health consequences resulting from improper waste sorting; examples of creative waste reduction and reuse strategies; and representations of successful community-level waste management initiatives. Animation development was coordinated by Suan Dusit University's Educational Technology Center in collaboration with environmental education specialists and primary school teachers to ensure developmental appropriateness and cultural relevance.

Local wisdom integration occurred through structured community engagement activities embedded within problem investigations. Students conducted interviews with community elders, documented traditional environmental practices through photographs and written narratives, and analyzed relationships between traditional wisdom and contemporary environmental challenges. In Bangkok, students explored Buddhist temple practices emphasizing simplicity, mindful consumption, and community-based composting initiatives. Suphanburi students investigated agricultural knowledge including organic composting derived from rice farming traditions, natural pest control methods reducing chemical waste, and traditional market practices minimizing packaging. Lampang students documented indigenous forest stewardship principles emphasizing resource conservation, circular use of natural materials, and traditional craft techniques creatively reusing materials.

This cultural integration served multiple pedagogical functions: enhancing personal and cultural relevance of environmental content; honoring community knowledge systems; bridging traditional wisdom with contemporary challenges; and strengthening students' environmental identity through connections between cultural heritage and environmental stewardship [22]. Students explicitly incorporated traditional practices into solution designs, adapting historical approaches to contemporary contexts (e.g., modernizing composting techniques for urban apartments, creating upcycled crafts using traditional artisan methods).

2.3.8. Control group instruction

Students assigned to the control condition received conventional instruction on waste management and environmental conservation aligned with standard Thai primary school curriculum guidelines. Control group instruction employed teacher-centered methodologies including: direct explanation of Thailand's four-bin waste-sorting system and rationales; textbook-based lessons on environmental conservation; teacher-led demonstrations of proper sorting techniques; completion of worksheets and quizzes assessing rule knowledge; and teacher-directed discussions of environmental issues. Control instruction was equivalent in duration (16 hours over four weeks) to ensure comparability in instructional time allocation, with differences confined to pedagogical approach rather than content coverage or time investment.

2.4. Data analysis

The data analysis process was structured into two main phases-descriptive analysis and inferential analysis-to address the study's research objectives and hypotheses comprehensively. Descriptive statistics were computed for all study variables, including measures of central tendency, dispersion, and distributional characteristics. Demographic information such as students' age, grade level, and school type was summarized using frequency distributions and percentages. Data normality was assessed through the Shapiro-Wilk test (for samples under 5,000), supported by visual inspections of histograms and Q-Q plots. Baseline equivalence between the experimental and control groups was evaluated using independent-samples t-tests for continuous variables and chi-square tests for categorical variables. Effect sizes were reported using Cohen's d, providing practical significance estimates of observed differences. Regional subsamples (Bangkok, Suphanburi, and Lampang) were analyzed separately to detect potential context-specific variations in demographic or baseline characteristics.

The primary analysis utilized a mixed-design analysis of variance (ANOVA), with time (pretest-posttest) as the within-subjects factor and group (experimental-control) and region (urban-rural) as between-subjects factors. This model enabled the examination of PBL's effectiveness while controlling for geographical and temporal influences. Effect sizes were reported using partial eta-squared (η^2p) for ANOVA results and Cohen's d for pairwise comparisons. Following Cohen's conventions, effect sizes were interpreted as small (η^2p=0.01, d=0.2), medium (η^2p=0.06, d=0.5), and large (η^2p=0.14, d=0.8). Tukey's honestly significant difference (HSD) post-hoc tests were employed to identify specific group differences for significant main or interaction effects.

3. RESULTS AND DISCUSSION

The study involved 400 primary school students drawn from three provinces: Bangkok (22.5%), Suphanburi (29.0%), and Lampang (48.5%). Among them, 136 students (34.0%) attended demonstration schools, while 264 students (66.0%) were enrolled in public schools. The majority of participants were 10-11 years old (83.5%), distributed across grade 4 (53.3%), grade 5 (45.0%), and grade 6 (1.8%). Subgroup analysis to examine whether PBL effectiveness varied by student characteristics, we conducted separate analyses by gender and baseline competency level. Gender differences independent t-tests revealed no significant gender differences in pretest scores ($p>0.05$). Post-intervention, both male and female students in the PBL group showed comparable gains (males: Δ knowledge=2.18, Δ behavior=1.72 and females: Δ knowledge=2.27, Δ behavior=1.83). The interaction between gender and intervention was nonsignificant (p=.421), suggesting PBL is equally effective regardless of gender. Students were classified as low, medium, or high baseline competency based on pretest knowledge scores (tertile split). Results indicated as: i) low baseline: Δ knowledge=2.89 (largest gains); ii) medium baseline: Δ knowledge=2.12; and iii) high baseline: Δ knowledge=1.68. This pattern suggests PBL particularly benefits struggling learners, though all groups improved significantly. Bootstrap mediation analysis (5,000 iterations) confirmed that knowledge gains mediated the relationship between PBL participation and behavioral change (indirect effect β=0.42, 95% CI=[0.35, 0.50]). Attitudes served as a secondary mediator (β=0.35, 95% CI=[0.28, 0.43]), supporting a sequential mediation model: PBL → knowledge → attitudes → behavior. Table 4 presents the comparison of pretest-posttest scores between experimental and control groups.

Table 4. Comparison of pretest–posttest scores between experimental and control groups

Variable	Group	Mean before		Mean after		Mean	t	p	η^2p/d	Summary/
		$\bar{x}$	SD	$\bar{x}$	SD	Difference				interpretation
Knowledge of	Experimental	5.12	1.27	7.35	0.89	+2.23	26.71	.001	1.52	Significantly increased
waste	Control	5.11	1.28	5.82	1.15	+0.71	9.84	.001		Supports H1, H2
Environmental	Experimental	3.90	0.90	4.49	0.71	+0.59	10.16	.001	0.68	Moderately improved
attitude	Control	3.89	0.93	3.97	0.89	+0.08	2.51	.05		Attitude
School	Experimental	2.34	0.89	4.12	0.78	+1.78	13.85	.001	1.67	Substantially increased
behavior	Control	2.31	0.92	2.67	0.95	+0.36				Actual behavior
Home	Experimental	2.18	0.95	3.89	0.82	+1.71	14.32	.001	1.71	Substantially increased
behavior	Control	2.15	0.98	2.43	0.89	+0.28				Actual behavior
Behavioral	Experimental	3.45	0.76	4.38	0.65	+0.93	8.02	.001	0.97	Strong increase in
intention	Control	3.44	0.78	3.67	0.82	+0.25				Behavioral intention

Students in the PBL group demonstrated significant gains across all domains. Knowledge of waste sorting increased by an average of 2.23 points (Cohen's d=1.52), indicating a very large effect. Environmental attitudes improved by 0.59 points (d=0.68), a moderate-to-large effect. Waste-sorting

behavior (both at school and at home) improved substantially, with effect sizes exceeding d=1.6, representing strong behavioral change. These results confirm hypotheses 1 and 2, demonstrating that PBL was significantly more effective than conventional teaching in promoting cognitive, affective, and behavioral outcomes related to environmental learning.

3.1. Subgroup analysis

To examine potential moderating effects of student characteristics on intervention effectiveness, supplementary analyses were conducted examining differential outcomes by gender and baseline competency level. Independent-samples t-tests revealed no significant gender differences in pretest scores across any outcome variable (all $p>0.05$). Post-intervention analyses indicated comparable improvement trajectories for male and female students within the experimental group. Male students demonstrated mean knowledge gains of 2.18 points (SD=0.94) and behavioral improvements of 1.72 points (SD=0.88), while female students showed gains of 2.27 points (SD=0.89) for knowledge and 1.83 points (SD=0.92) for behavior. The interaction term between gender and intervention condition was nonsignificant ($F(1,396)=0.65$, $p=0.421$, $\eta^2p=0.002$), indicating equivalent PBL effectiveness regardless of gender.

Baseline competency was operationalized by categorizing students into tertiles based on pretest knowledge scores: low (≤4.0), medium (4.1-5.9), and high (≥6.0). Results revealed differential gain patterns, with low-baseline students demonstrating the largest knowledge improvements (M=2.89, SD=1.12), followed by medium-baseline (M=2.12, SD=0.87) and high-baseline students (M=1.68, SD=0.76), $F(2,197)=8.34$, $p<0.001$, $\eta^2p=0.08$. Post-hoc analyses using Tukey's HSD confirmed significant differences between low- and high-baseline groups ($p<0.001$), suggesting that PBL conferred particular benefits for students entering with lower initial competency. However, all subgroups demonstrated statistically significant improvements (all $p<0.001$), confirming broad intervention effectiveness across the competency spectrum.

Mediation pathway analysis further clarified the mechanisms underlying behavioral change. Bootstrap analysis with 5,000 iterations confirmed that knowledge gains significantly mediated the relationship between PBL participation and behavioral outcomes (indirect effect $\beta=0.42$, 95% CI=[0.35, 0.50], $p<0.001$). Environmental attitudes served as a secondary mediator (indirect effect $\beta=0.35$, 95% CI=[0.28, 0.43], $p<0.001$). Sequential mediation modeling supported the pathway: PBL exposure → knowledge acquisition → attitude formation → behavioral enactment, consistent with the theoretical predictions of the KAP framework [15]. These findings provide empirical clarification of the cognitive and affective processes through which problem-based pedagogy influences sustainable behavior development.

ANOVA results as in Table 5 revealed a significant interaction between group and time, $F(1,396)=285.67$, $p<0.001$, $\eta^2_p=0.42$, indicating a strong intervention effect of PBL. No significant differences were found across regions ($F(2,396)=2.18$, $p=0.114$), suggesting consistent effectiveness across urban and rural schools. The three-way interaction (time×group×region) was also nonsignificant, confirming the robustness and transferability of the intervention model.

Table 5. Summary of statistical analysis results

Analytical aspect	Statistic	p-value	Effect size (η^2p)	Summary of findings
Group×time (PBL vs. Traditional)	$F(1,396)=285.67$	.001	0.42	PBL showed a significantly superior effect
Region (Bangkok-Suphanburi-Lampang)	$F(2,396)=2.18$	.114	0.01	No significant differences among regions
Time×group×region	$F(4,396)=0.67$	.512	–	No significant three-way interaction
Mediation by attitude	β(indirect)=0.35 (95% CI 0.28-0.43)	.001	–	Attitude partially mediated the relationship (partial mediation)

Mediation analysis showed that environmental attitudes partially mediated the relationship between knowledge and behavior (β_indirect = 0.35, 95% CI=[0.28, 0.43]), providing empirical support for the KAP Model. This finding suggests that attitude transformation serves as a key mechanism linking cognitive gains to sustainable behavioral outcomes. The observed improvements in knowledge, attitudes, and behaviors may be explained through several underlying psychological mechanisms. First, self-efficacy theory [11] suggests that PBL enhanced students' confidence in their environmental capabilities through mastery experiences. By successfully completing authentic waste-sorting tasks, students developed stronger beliefs in their ability to enact pro-environmental behaviors, which subsequently influenced their behavioral intentions and actual performance [21]. Second, the development of environmental responsibility appeared to emerge through the intervention's emphasis on personal accountability and consequence awareness. Students who investigated real community waste problems likely experienced heightened moral engagement and internalized

environmental stewardship values [23], consistent with value-belief-norm theory's predictions regarding environmentally significant behavior.

Furthermore, the collaborative structure of PBL may have activated social identity processes and peer normative influences. Working collectively to address shared environmental challenges fostered group-based environmental identities and established pro-environmental norms within peer networks [24], creating social accountability mechanisms that reinforced individual behavioral change. The affective dimension of learning—characterized by emotional responses to environmental degradation observed during problem investigation—may have served as an additional motivational force driving attitude formation and behavioral commitment. These psychological processes warrant explicit empirical investigation in future research through direct measurement of self-efficacy, environmental identity, moral emotions, and social norms as potential mediators of PBL's effects on environmental learning outcomes.

The results reaffirm the effectiveness of PBL as a transformative pedagogical strategy. Consistent with Dale's cone of experience and Kolb's experiential learning theory [15], [16], the hands-on, inquiry-based nature of PBL facilitated deep conceptual understanding and authentic engagement with environmental issues. The significant behavioral changes observed align with Bloom's KAP framework [17], emphasizing the sequential integration of knowledge, attitudes, and practice in achieving sustainable learning outcomes.

Furthermore, the integration of local wisdom into animated learning media may have supported student engagement and comprehension of culturally relevant content, thereby strengthening the relevance of the learning experience [22], [24], [25]. In this study, the animated media appeared to function primarily as an instructional scaffold, providing foundational knowledge, activating prior knowledge, and stimulating curiosity prior to problem investigation. However, the present study was designed to evaluate the effectiveness of the PBL-based intervention as an integrated pedagogical package rather than to isolate the independent effect of specific technological components. Therefore, the significant gains observed should be interpreted primarily as evidence of the effectiveness of the PBL-centered instructional design, with digital media serving as a supportive element rather than an independently tested causal factor. Future research employing dismantling designs could clarify the relative contributions of PBL structure and digital media components.

The integration of explicit strategy instruction within PBL frameworks may have contributed to observed knowledge transfer and behavioral enactment. Teaching students metacognitive strategies for approaching complex tasks may enhance their ability to systematically apply knowledge in novel contexts. In this study, students received explicit guidance in problem-solving strategies including systematic data collection, evidence-based reasoning, and solution evaluation. This strategic scaffolding likely facilitated the translation of acquired waste-sorting knowledge into consistent behavioral practice, as students possessed not only domain knowledge but also procedural knowledge regarding how to apply that knowledge in varied situations. Future research should explicitly measure strategy use as a potential mediator of PBL's effects on behavior change. Together, these findings suggest that combining PBL with contextually designed, interactive learning media and guided strategy use creates authentic and impactful learning experiences, reinforcing both attitudinal internalization and practical skills.

The mediating role of attitudes underscores the importance of affective engagement in environmental education. As Wiek *et al*. [10] and Schmidt *et al*. [12] note, durable behavioral change depends on the internalization of environmental values, not merely on information acquisition. Bulkani *et al*. [22] further demonstrate that learning media incorporating local wisdom can enhance student engagement and understanding, highlighting the importance of culturally relevant and context-sensitive instructional tools. Similarly, the use of gather-process-apply-share (GPAS) 5 Steps with board game activities has been shown to significantly improve students' analytical thinking, academic achievement, and satisfaction with the learning process [26]. The present findings extend this evidence by showing that PBL, particularly when coupled with locally contextualized problem scenarios and interactive learning media, nurtures attitudinal internalization in early learners, fostering both environmental awareness and active learning behaviors.

No significant differences in intervention outcomes among Bangkok, Suphanburi, and Lampang suggest that PBL is culturally and geographically adaptable. The use of locally contextualized problem scenarios likely enhanced learners' sense of relevance and ownership, supporting Monroe *et al*.'s [14] argument that contextual learning mitigates cultural disparities in environmental education. This suggests that PBL can serve as a scalable model for nationwide implementation, especially within the Thai primary curriculum. The observed behavioral changes, particularly the substantial improvements in actual home and school sorting practices (Cohen's $d>1.6$), represent concrete contributions toward SDG 12's waste reduction targets [27]. Early environmental education creates multiplier effects as children influence household

practices and carry sustainable habits into adulthood [28] potentially generating intergenerational behavior change extending beyond the immediate intervention cohort.

3.2. Limitations and considerations of potential confounding factors

While this study employed rigorous quasi-experimental methodology with random group assignment and multi-site data collection, several potential confounding influences warrant acknowledgment. First, teacher-level variability may have influenced intervention implementation despite standardized training protocols. All PBL facilitators completed intensive 24-hour professional development addressing theoretical foundations, facilitation techniques, and fidelity monitoring. Classroom observations conducted by independent raters confirmed 85% adherence to prescribed protocols (range 80-92%). However, individual teaching styles, enthusiasm levels, and prior environmental attitudes may have introduced unmeasured variance in intervention delivery. Future research should employ multilevel modeling to formally partition teacher-level effects and examine facilitator characteristics as potential moderators of intervention effectiveness.

Second, classroom environmental infrastructure varied across study sites and may have differentially supported behavioral enactment. Schools with pre-existing recycling systems, visible waste-sorting signage, and accessible disposal facilities potentially amplified intervention effects by reducing behavioral barriers. The study did not systematically document these contextual factors, representing a limitation in understanding environmental supports for behavior change. Future investigations should incorporate systematic audits of school environmental characteristics and examine infrastructure availability as a potential moderator.

Third, parental environmental attitudes and household waste management practices likely influenced students' home behaviors, particularly given the likely bidirectional influence between children and parents in environmental domains. While randomization procedures should have distributed parental influence equally across conditions, family-level characteristics were not assessed. Incorporating family environmental practices as covariates or implementing complementary parent education components could enhance intervention effects and provide more complete understanding of behavior change processes.

Fourth, temporal factors including seasonal variation and concurrent environmental events may have affected student awareness and motivation. Data collection occurred across different months at the three study sites (Bangkok: March-April; Suphanburi: April-May; and Lampang: May-June), potentially exposing students to different environmental conditions, pollution episodes, or local waste management campaigns. While no major environmental events were identified during the study period through retrospective media analysis, unmeasured temporal influences cannot be definitively ruled out.

Fifth, self-reported behavioral measures may be subject to social desirability bias, particularly given the explicit focus on environmental education. To partially address this concern, a validation subsample ($n=60$) underwent direct behavioral observations during school lunch periods by research assistants blind to group assignment. Observed waste-sorting accuracy correlated significantly with self-reported school behavior scores ($r=0.67$, $p<0.001$), providing convergent validity evidence. Additionally, parent ratings of students' home behaviors ($n=120$) demonstrated moderate agreement with student self-reports ($\kappa=0.58$), suggesting reasonable accuracy despite potential response biases. Nevertheless, future research should prioritize unobtrusive behavioral measurement strategies, including automated monitoring of waste-bin usage and long-term tracking of actual recycling rates.

Finally, the relatively brief follow-up period (four weeks post-intervention) limits conclusions regarding long-term behavioral sustainability. While short-term maintenance was demonstrated, environmental behaviors may plausibly decay over extended periods without continued reinforcement. Longitudinal studies with 6- to 12-month follow-up assessments are needed to establish whether PBL-induced behavioral changes persist and potentially generalize to new environmental domains. Despite these limitations, the convergence of large effect sizes, consistent cross-site findings, and theoretically coherent mediation patterns provides substantial confidence in the study's core conclusions regarding PBL's effectiveness in environmental education.

While the results are robust, several limitations merit attention. Self-reported behavioral data may be subject to social-desirability bias; future research should incorporate longitudinal behavioral observations. The short follow-up period limits insight into long-term behavioral sustainability; future studies should employ extended tracking. Comparative studies involving other innovative models (e.g., game-based learning (GBL)) [1] could further elucidate the relative pedagogical value of PBL. Future research may also explore hybrid PBL-digital learning models or artificial intelligence (AI)-assisted environmental simulations, aligning with global trends toward sustainability-driven educational technology.

4. CONCLUSION

This study provides robust empirical evidence supporting the effectiveness of PBL in enhancing knowledge, environmental attitudes, and waste-sorting behaviors among primary school students in Thailand. Students who participated in PBL exhibited significantly greater gains than those receiving traditional instruction, with particularly large effect sizes in both knowledge acquisition and behavioral performance. Moreover, attitudes were found to partially mediate the relationship between knowledge and behavior, confirming the theoretical validity of the KAP model.

The absence of regional differences in outcomes indicates that PBL is adaptable and effective across urban and rural contexts, highlighting its potential for nationwide educational reform. These findings contribute to the global discourse on sustainability-oriented pedagogy, demonstrating that experiential and collaborative learning approaches can cultivate early environmental responsibility. Furthermore, the results establish a foundation for developing innovative educational technologies, such as game-based learning tools and smart waste-bin systems, to reinforce environmental literacy and long-term behavioral change. Overall, this research reinforces the role of PBL as a scalable framework for achieving the United Nations Sustainable Development Goals (SDG 4: quality education; SDG 12: responsible consumption and production). By embedding authentic environmental problem-solving in classroom practice, educators can empower young learners to become agents of sustainable change-a cornerstone of future-oriented education.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest related to the design, implementation, or reporting of this study.

INFORMED CONSENT

Informed consent was obtained from all students, parents, and school administrators prior to participation. Each participant received a clear explanation of the research objectives, procedures, and confidentiality measures before signing a written consent form.

ETHICAL APPROVAL

This research adhered to the ethical principles of the Helsinki Declaration and the Human Research Ethics Policy of Suan Dusit University. Ethical approval was granted by the Human Research Ethics Committee, Research and Development Institute, Suan Dusit University, under Approval Code: SDU-RDI-SHS 2022-049.

DATA AVAILABILITY

The datasets generated and analyzed during the current study are available from the corresponding author, [SP], upon reasonable request. Due to ethical considerations and privacy protection for student participants, raw data are not publicly accessible.

REFERENCES

[1] S. de Freitas, "Are games effective learning tools? A review of educational games," *Educational Technology & Society*, vol. 21, no. 2, pp. 74–84, 2018.

[2] B. Gros, "Digital games in education: the design of games-based learning environments," *Journal of Research on Technology in Education*, vol. 40, no. 1, pp. 23–38, 2007, doi: 10.1080/15391523.2007.10782494.

[3] N. M. Ardoin, A. W. Bowers, N. W. Roth, and Nicole Holthuis, "Environmental education and K-12 student outcomes: a review and analysis of research," *The Journal of Environmental Education*, vol. 49, no. 1, 2018, doi 10.1080/00958964.2017.1366155.

[4] M. Barth, *Implementing sustainability in higher education: learning in an age of transformation*, New York, NY: Routledge, 2015.

[5] Pollution Control Department, Ministry of Natural Resources and Environment, "Thailand state of pollution report 2021," Bangkok, Thailand, 2022.

[6] K. F. Hew and T. Brush, "Integrating technology into K-12 teaching and learning: current knowledge gaps and recommendations for future research," *Educational Technology Research and Development*, vol. 55, no. 3, pp. 223–252, 2007, doi: 10.1007/s11423-006-9022-5.

[7] R. M. Tamim, R. M. Bernard, E. Borokhovski, P. C. Abrami, and R. F. Schmid, "What forty years of research says about the impact of technology on learning: a second-order meta-analysis and validation study," *Review of Educational Research*, vol. 81, no. 1, pp. 4–28, 2011, doi: 10.3102/0034654310393361.

[8] C. E. Hmelo-silver "Problem-based learning: what and how do students learn?" *Educational Psychology Review. Springer*, vol. 16, no. 3, pp. 235–266, 2016, doi: 10.1023/B:EDPR.0000034022.16470.f3.

[9] J. R. Savery, "Overview of problem-based learning: definitions and distinctions," *Interdisciplinary Journal of Problem-Based Learning*, vol. 1, no. 1, pp. 9–20, 2006.

[10] A. Wiek, L. Withycombe, and C. L. Redman, "Key competencies in sustainability: a reference framework for academic program development," *Sustainability Science*, vol. 6, no. 2, pp. 203–218, 2011, doi: 10.1007/s11625-011-0132-6.

[11] A. Bandura, "Self-efficacy: toward a unifying theory of behavioral change," *Psychological Review*, vol. 84, no. 2, pp. 191–215, 1977, doi: 10.1037//0033-295x.84.2.191.

[12] H. Schmidt, J. Rotgans, and E. Yew, "The process of problem-based learning: what works and why," *Medical Education*, vol. 45, no. 8, 2011, doi: 10.1111/j.1365-2923.2011.04035.x.

[13] H. Kopnina, "Education for the future? Critical evaluation of education for sustainable development goals," *Journal of Environmental Education*, vol. 51, no. 4, pp. 280–291, 2020, doi: 10.1080/00958964.2019.1710444.

[14] M. C. Monroe, R. R. Plate, A. Bowers, and W. A. Chaves, "Identifying effective climate change education strategies: a systematic review of the research.," *Environmental Education Research*, vol. 25, no. 6, pp. 791–812, 2017, doi: 10.1080/13504622.2017.1360842.

[15] D. A. Kolb, *Experiential learning: experience as the source of learning and development*. Englewood Cliffs: Prentice Hall, 1984.

[16] J. S. Bruner, "The act of discovery," *Harvard Educational Review*, vol. 31, no. 1, 1961.

[17] B. S. Bloom, *Taxonomy of educational objectives: the classification of educational goals. Handbook I: cognitive domain*, Lon: Longmans, 1956.

[18] United Nations, "Transforming our world: the 2030 agenda for sustainable development," A/RES/70/1, 2015.

[19] E. L. Deci and R. M. Ryan, "The 'what' and 'why' of goal pursuits: human needs and the self-determination of behavior," *Psychological Inquiry*, vol. 11, no. 4, pp. 227–268, 2000, doi: 10.1207/S15327965PLI1104_01.

[20] B. B. Frey, "Statistical power analysis for the behavioral sciences," *The SAGE Encyclopedia of Research Design*, 2022, doi: 10.4135/9781071812082.n600.

[21] J. D. Creswell and J.W. Creswell, *Research design qualitative, quantitative, and mixed methods approaches*. 5th ed, Los Angeles: Sage, 2018.

[22] Bulkani, M. Fatchurahman, H. Adella, and M. A. Setiawan, "Development of animation learning media based on local wisdom to improve student learning outcomes in elementary schools," *International Journal of Instruction*, vol. 15, no. 1, pp. 55–72, 2022, doi: 10.29333/iji.2022.1514a.

[23] P. Wesley Schultz and L. Zelezny, "Values as predictors of environmental attitudes: evidence for consistency across 14 countries," *Journal of Environmental Psychology*, vol. 19, no. 3, pp. 255–265, 1999, doi: 10.1006/jevp.1999.0129.

[24] P. C. Stern, "Toward a coherent theory of environmentally significant behavior," *Journal of Social Issues*, vol. 56, no. 3, pp. 407–424, 2000.

[25] K. S. Fielding and M. J. Hornsey, "A social identity analysis of climate change and environmental attitudes and behaviors: insights and opportunities," *Frontiers in Psychology*, vol. 7, 2016, doi: 10.3389/fpsyg.2016.00121.

[26] J. H. Flavell, "Metacognition and cognitive monitoring: a new area of cognitive-developmental inquiry," *American Psychologist*, vol. 34, no. 10, pp. 906–911, 1979, doi: 10.1037//0003-066x.34.10.906.

[27] D. Weerapan and K. Wongyai, "The effects of board games activities on Khid-Khad-Yaek with GPAS 5 Step to promote thinking skills," (in Thai), *Journal of Global Perspectives in Humanities and Social Sciences*, vol. 18, no. 2, pp. 45–60, May–Aug. 2024.

[28] A. Kollmuss and J. Agyeman, "Mind the gap: why do people act environmentally and what are the barriers to pro-environmental behavior," *Environmental Education Research*, vol. 8, no. 3, pp. 239–260, 2002, doi: 10.1080/13504620220145401.

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