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RESEARCH ARTICLE Setiawan et al.

Upcycled Science Learning Media for Elementary Students' Conceptual Understanding and Environmental Literacy: A Design and Development Study

Bramianto Setiawan[1,*], Septian Mukhlis[2], Ahmad Fauzi[3]

[1] Department of Elementary Teacher Education, Universitas Pelita Bangsa, Bekasi, Indonesia

*Corresponding author: sbramianto@pelitabangsa.ac.id

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Abstrak

Banyak sekolah dasar di negara berkembang kekurangan alat peraga sains, sementara masyarakat di sekitarnya menghasilkan sampah padat yang terus meningkat. Penelitian ini mengembangkan media pembelajaran sains berbasis sampah daur ulang (EcoSci Kit: lima media dari botol PET, tutup botol, karton susu, kaleng, dan plastik untuk topik campuran, rangkaian listrik, cahaya, bunyi, dan siklus air) serta menguji kevalidan, kepraktisan, dan keefektifannya bagi siswa kelas V. Penelitian pengembangan ini mengikuti model ADDIE. Enam ahli memvalidasi media, 32 siswa dan empat guru mengikuti uji coba terbatas, dan 122 siswa dari empat sekolah dasar negeri di Indonesia terlibat dalam desain kuasi-eksperimen pretest–posttest dengan kelompok kontrol selama enam minggu (12 pertemuan). Media dinyatakan valid dan sangat praktis. Kelompok eksperimen memperoleh peningkatan pemahaman konsep yang lebih tinggi daripada kelompok kontrol (N-gain 0,53 vs 0,30; $F(1, 119) = 58,47$; $p < 0,001$; $\eta p2 = 0,33$) dan literasi lingkungan yang lebih tinggi ($F(1, 119) = 47,12$; $p < 0,001$; $\eta p2 = 0,28$). dengan selisih deskriptif terbesar pada sikap terhadap sampah. Kebaruan penelitian ini terletak pada pengujian terkontrol atas hasil kognitif dan afektif sekaligus. Karena menggunakan kelas utuh di satu kabupaten, temuan perlu dikonfirmasi melalui desain acak klaster dan pengukuran perilaku nyata.

Kata kunci: Literasi Lingkungan; Media Pembelajaran; Daur Ulang; Pemahaman Konsep; Sains Sekolah Dasar.

Abstract

Many elementary schools in developing countries lack science apparatus, while their communities generate rising amounts of solid waste. This study developed upcycled science learning media (the EcoSci Kit: five media made from PET bottles, bottle caps, milk cartons, cans, and plastic, covering mixtures, circuits, light, sound, and the water cycle) and examined their validity, practicality, and effectiveness for grade 5 students. The design and development research followed the ADDIE model. Six experts validated the media, 32 students and four teachers joined a limited trial, and 122 students from four Indonesian public elementary schools took part in a six-week (twelve-lesson) quasi-experimental pretest–posttest control group design. The kit was rated valid and highly practical. The experimental group gained more than the control group in conceptual understanding (N-gain 0.53 vs 0.30; $F(1, 119) = 58.47$, $p < .001$, $\eta p2 = .33$) and in environmental literacy ($F(1, 119) = 47.12$, $p < .001$, $\eta p2 = .28$). with the largest descriptive gain in attitudes toward waste. The study is novel in testing cognitive and affective outcomes together under controlled conditions. Because intact classes from one district were used, the findings should be confirmed through cluster-randomised designs and observed behaviour.

Keywords: Environmental Literacy; Learning Media; Recycling; Conceptual Understanding; Elementary School Science.

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1. INTRODUCTION

Children learn science most deeply when they can handle objects, test their ideas, and observe the results (Hofstein & Lunetta, 2004; Freeman et al., 2014). The elementary years are especially important because early conceptions of matter, light, sound, and electricity tend to persist and can harden into misconceptions that later instruction struggles to undo (Posner et al., 1982; Vosniadou, 1994). Yet many elementary schools in low- and middle-income countries have little or no science apparatus, and international assessments continue to show wide gaps in science achievement between and within countries (Mullis et al., 2020; OECD, 2023). In such classrooms, teachers often fall back on textbook reading and pictures, which leaves abstract concepts abstract.

The same communities face a growing waste problem. Global municipal solid waste is projected to rise from 2.01 billion tonnes in 2016 to 3.40 billion tonnes by 2050 (Kaza et al., 2018). Plastic accounts for a large share of this burden: most of the plastic ever produced has accumulated in landfills or the natural environment (Geyer et al., 2017), and millions of tonnes of land-based plastic waste enter the oceans every year, with Indonesia among the largest contributors of mismanaged plastic waste (Jambeck et al., 2015). Bottles, cartons, cans, and bottle caps are therefore abundant around the very schools that lack equipment. In Indonesia, the problem is acute at the school level: a survey of public elementary schools in Padang found that only about 60% of the required teaching aids and 52.5% of science kits were available, and that only about 40% of teachers used science kits in their lessons (Satria & Sari, 2018). At the same time, the national waste information system recorded 33.79 million tonnes of waste generated in 2024, about half of it from households (Kementerian Lingkungan Hidup, 2025). Our own preliminary observation in the target district confirmed this picture (see Needs Analysis): the participating schools owned apparatus for only 27% of grade 5 science topics, while PET bottles alone made up 41% of the recyclable waste on school grounds.

Turning this waste into science learning media addresses both problems at once. It lowers the cost of hands-on inquiry, as earlier work on low-cost and improvised apparatus has shown (Syahrial et al., 2026), and it allows children to experience the logic of the circular economy directly (Ellen MacArthur Foundation, 2013). It also responds to the agenda of Education for Sustainable Development (ESD), which asks schools to develop knowledge, values, and action competencies together rather than separately (UNESCO, 2017, 2020; Wiek et al., 2011). Childhood is a sensitive period for forming environmental dispositions, and direct, material experiences are thought to shape later pro-environmental behaviour (Sobel, 1996; Chawla & Cushing, 2007; Otto & Pensini, 2017). In Indonesia, this agenda is embodied in the Kurikulum Merdeka, where the IPAS subject integrates science with social and environmental issues, and in the Pancasila Student Profile, particularly the dimensions of critical reasoning (bernalar kritis), creativity (kreatif), and global diversity, which includes care for the environment, as well as the P5 theme of sustainable lifestyles (Gaya Hidup Berkelanjutan).

Despite this promise, the evidence base remains thin. Studies of waste-based teaching aids are mostly

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descriptive or qualitative (Parejo et al., 2021; Wahyudi et al., 2024; Syahrial et al., 2026), rarely report systematic expert validation, and seldom compare outcomes with a control group. Reviews of environmental education also note that cognitive and affective outcomes are usually measured in separate studies, which makes it difficult to know whether a single intervention can serve both science learning and sustainability goals (Ardoin & Bowers, 2020; Ardoin et al., 2020; Naila et al., 2025). Evidence at the elementary level, where both conceptual foundations and environmental attitudes are formed, is particularly scarce. Many Indonesian development studies of recycled media stop at validity and practicality, or test effectiveness with a single-group pretest–posttest design. The present study differs in three respects: it targets five curriculum-aligned concepts with one coherent kit, it measures conceptual understanding with a two-tier diagnostic test rather than a conventional achievement test, and it compares cognitive and affective outcomes against a control group taught with the same 5E lesson plans.

This study addresses that gap by developing and testing an upcycled science kit for grade 5 students in Indonesia. It addresses three research questions. RQ1: How valid are the developed media are according to content and media experts? RQ2: How practical they are according to elementary teachers and students? RQ3: Do they improve students' conceptual understanding and environmental literacy compared with conventional instruction? In answering these questions, the study contributes a development protocol documented in enough detail to be replicated (Appendix A), child-appropriate instruments, and controlled evidence that low-cost upcycled media can advance science learning and ESD at the same time.

2. LITERATURE REVIEW

2.1. Concrete Experience and Constructivism in Elementary Science

Children aged seven to eleven are in what Piaget (1970) described as the concrete operational stage: they reason well about objects they can see and manipulate but find purely verbal abstractions difficult. Dale's (1969) Cone of Experience similarly places direct, purposeful experience at the base of meaningful learning. Social constructivism adds that understanding grows through guided talk with teachers and peers (Vygotsky, 1978). Manipulable media therefore offer young learners both an object to act upon and a shared focus for discussion, and empirical work supports this view: a meta-analysis found that physical manipulatives improve learning, especially when instruction is guided (Carbonneau et al., 2013), and experimental studies show that manipulating physical apparatus supports students' conceptual understanding in science (Olympiou & Zacharia, 2012).

2.2. Guided Inquiry and Cognitive Engagement

Hands-on activity alone does not guarantee learning. Unguided discovery can overload novice learners and leave misconceptions intact (Kirschner et al., 2006; Mayer, 2004). Meta-analytic evidence shows that inquiry is effective when it is accompanied by appropriate guidance (Lazonder & Harmsen, 2016), and recent syntheses argue for combining inquiry with explicit instruction rather than treating them as rivals (de Jong et al., 2023). The ICAP framework explains why: learning rises as engagement moves from passive to

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active, constructive, and interactive modes (Chi & Wylie, 2014). The 5E instructional model offers a practical structure for keeping inquiry guided (Bybee, 2014), and it was therefore used to frame every lesson in this study. In this study the media were embedded in each 5E phase as follows. In Engage, the teacher posed a puzzling question and elicited predictions on the worksheet. In Explore, groups of four to five students assembled and tested the device (e.g., the periscope) following a step sheet. In Explain, groups compared observations with predictions and the teacher introduced the scientific explanation. In Elaborate, students modified the device to test a new condition (e.g., changing mirror angles). In Evaluate, students answered reflective questions and dismantled the device for reuse. The control group followed the same phases, but Explore and Elaborate used textbook pictures and teacher demonstrations instead of student-built devices.

2.3. Conceptual Change in Young Learners

Conceptual change theory holds that learners restructure prior ideas when they become dissatisfied with them and find a new conception intelligible, plausible, and fruitful (Posner et al., 1982). Children's intuitive models, such as the belief that vision works by light leaving the eye, are internally coherent and resistant to change (Vosniadou, 1994). Two-tier diagnostic tests, which ask for both an answer and the reasoning behind it, make such models visible and allow researchers to distinguish genuine understanding from guessing (Treagust, 1988).

2.4. Environmental Literacy and Education for Sustainable Development

Environmental literacy encompasses ecological knowledge, environmental affect, cognitive skills, and responsible behaviour (Hollweg et al., 2011). Knowledge alone rarely changes behaviour (Kollmuss & Agyeman, 2002); emotional connection and direct experience play a larger role, especially in childhood (Chawla & Cushing, 2007; Ardoin & Bowers, 2020). A recent Indonesian study confirmed this pattern, finding that elementary students' attitudes predicted their reduce–reuse–recycle behaviour more strongly than their knowledge did (Gunamantha & Dantes, 2025). ESD frameworks therefore call for learning that integrates these components (UNESCO, 2017, 2020), although schools often struggle to translate this goal into everyday practice (Stevenson, 2007). The present study measured three of these components: knowledge, attitude (affect), and behavioural intention as a proxy for behaviour. Cognitive skills such as issue identification and action planning were not measured, because their assessment requires performance tasks that are difficult to administer reliably to ten-year-olds within a six-week intervention; this is acknowledged as a limitation.

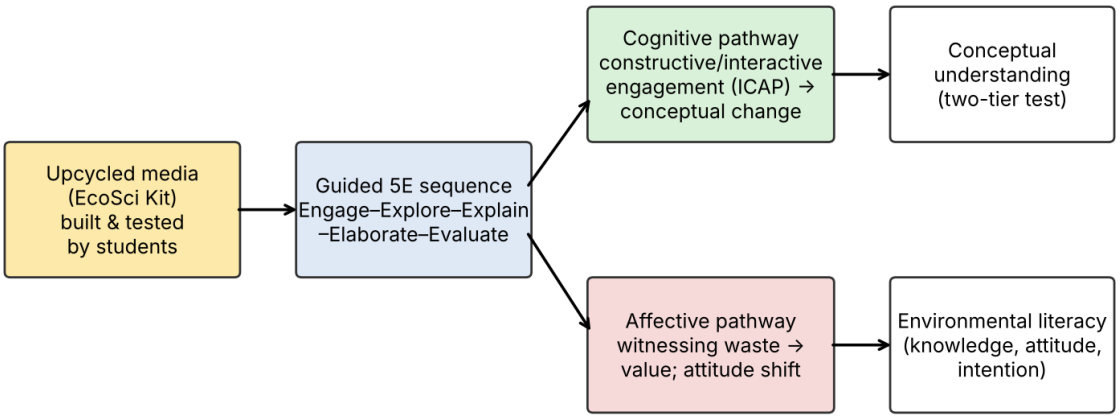
2.5. Waste-Based Learning Media

Waste-based media sit at the intersection of these strands. A case study in Ghana showed that lessons built around plastic waste raised children's awareness of plastic pollution while producing reusable classroom materials (Parejo et al., 2021). In Indonesia, development studies of recycled media have reported positive student responses or descriptive improvements (Wahyudi et al., 2024; Syahrial et al., 2026), but few

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have used a control group or measured affective outcomes. Such work suggests a dual pathway. In the cognitive pathway, manipulating upcycled media within guided inquiry supports conceptual change in science content. In the affective pathway, witnessing waste transformed into useful tools shifts children's attitudes toward waste and their intention to reduce, reuse, and recycle. The present study tests both pathways within a single controlled design. The dual pathway is summarised in Figure 1. Notably, the pathways are offered as a theoretical rationale; the present design tests the outcomes of each pathway, not the mediating mechanisms. Based on this framework, two hypotheses were tested: H1, students taught with the EcoSci Kit achieve higher conceptual understanding than control students after controlling for pretest scores; and H2, they achieve higher environmental literacy than control students after controlling for pretest scores.



Pathways are hypothesised; this study tests the outcomes, not the mediating mechanisms.

Figure 1. Conceptual framework of the dual pathway (hypothesised)

3. METHOD

3.1. Research Design

This study employed design and development research (Richey & Klein, 2007; Plomp & Nieveen, 2013) following the ADDIE model (Branch, 2009), and tested effectiveness through a quasi-experimental pretest–posttest non-equivalent control group design. The analysis phase combined interviews with eight teachers, classroom observation, an inventory of apparatus in four schools, and an audit of waste on school grounds. In the design phase, grade 5 learning outcomes for Natural and Social Science (IPAS) in Indonesia's Kurikulum Merdeka were mapped onto locally available waste materials, and blueprints and 5E worksheets were drafted. The development phase produced prototypes that were validated by experts and revised. Implementation began with a limited trial to establish practicality and continued with a six-week field test of twelve 70-minute lessons. Evaluation was formative throughout and summative at the end of the field test.

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3.2. The EcoSci Kit

The EcoSci Kit consists of five media, each built from common household and school waste and aligned with a grade 5 science concept, as summarised in Table 1. Every kit cost approximately IDR 85,000 (about USD 5.40) in consumables, compared with roughly IDR 1,450,000 (about USD 92) for commercial equivalents. Safety rules excluded batteries above 3 V, unprotected sharp edges, and hazardous electronic components, and all mirror edges were sealed with tape.

Table 1. Components of the EcoSci Kit

Media	Waste materials	Science concept (grade 5)
Bottle water filter	PET bottles, sand, gravel, used cloth, charcoal	Separating mixtures; clean water
Bottle-cap circuit board	Bottle caps, cardboard, aluminium foil, salvaged wires, LEDs	Simple circuits; conductors and insulators
Milk-carton periscope	Milk cartons, mirror pieces with taped edges	Light travels in straight lines and reflects
Can-and-string telephone	Tin cans, plastic cups, string	Sound travels through solids
Bottle water-cycle terrarium	PET bottles, soil, plastic film, ice	Evaporation, condensation, and the water cycle

3.3. Participants

Six experts validated the media: three science-content specialists, two instructional media specialists, and one elementary pedagogy specialist, each with at least ten years of experience. The limited trial involved 32 grade 5 students and four teachers from a school that did not take part in the field test. The field test involved 122 grade 5 students aged 10 to 11 years (63 girls and 59 boys) from four public elementary schools in Kabupaten Bekasi, Indonesia. Because random assignment of individual pupils was not feasible, intact classes were assigned either to the experimental group (n = 62), taught with the EcoSci Kit, or to the control group (n = 60), taught with textbooks, pictures, and teacher demonstrations. Each school contributed one grade 5 classes; classes were allocated so that two schools were assigned to the experimental condition and two to the control condition, with one class per school, giving 2 experimental and 2 control classes in total. All lessons were taught by the regular classroom teachers (four teachers), who attended a two-hour briefing on the lesson plans; the researchers did not teach. Implementation fidelity was monitored with an observation sheet covering the five 5E phases, completed by a trained observer in 50 of lessons in both groups, with mean fidelity of 94% (experimental) and 92% (control). Both groups followed identical 5E lesson plans, so the media were the main planned difference between conditions; however, because experimental students built and manipulated their own devices whereas control students observed demonstrations, the contrast also involved a difference in the level of active engagement, and the treatment is best understood as the media together with the hands-on activity they enable. Six students were absent from the pretest or posttest and were excluded, leaving the analysed sample reported above.

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3.4. Instruments

Five instruments were used, as presented in Table 2. The conceptual understanding test followed Treagust's (1988) procedure for two-tier items, and an item was scored as correct only when both the answer and the reason were correct. The environmental literacy questionnaire was adapted for children from the framework of Hollweg et al. (2011) and comprised knowledge, attitude, and behavioural intention subscales. Child-friendly wording and pictorial response scales were piloted with 30 students, and all student instruments were read aloud to the class. Content validity of the two-tier test and the questionnaire was established by three experts, with item Aiken's V ranging from 0.83 to 1.00. The two-tier test followed a blueprint of four items per topic; item difficulty indices ranged from 0.32 to 0.78 and discrimination indices from 0.29 to 0.61. For the questionnaire, the pilot sample (n = 30) was too small for factor analysis, so construct validity was supported by corrected item–total correlations (range 0.36–0.68) and subscale reliabilities (knowledge α = 0.79, attitude α = 0.84, intention α = 0.81); a confirmatory factor analysis with a larger sample is recommended for future work.

Table 2. Research instruments

Instrument	Items	Scale	Reliability
Expert validation sheet	20	1–4	Aiken's V per item
Teacher practicality questionnaire	15	1–5 Likert	α = .85
Student practicality questionnaire (pictorial)	12	1–4 smiley faces	α = .81
Two-tier conceptual understanding test	20	0–100	KR-20 = .82
Environmental literacy questionnaire	24	1–5	α = .87

3.5. Data Analysis

Content validity was calculated with Aiken's V, as shown in (1), where $s = r - l_0$, r is a rater's score, l_0 is the lowest possible score, n is the number of raters, and c is the number of categories. With six raters and four categories, items with $V \geq 0.78$ were regarded as valid (Aiken, 1985).

$$V = \Sigma s \,/\, [n(c - 1)] \tag{1}$$

Practicality was expressed as the percentage of the maximum possible score, with values of 81% or above categorised as highly practical. Learning gains were computed with Hake's (1998) normalised gain in (2) and interpreted as low ($g < 0.30$), medium ($0.30 \leq g \leq 0.70$), or high ($g > 0.70$); values were rounded to two decimals.

$$\langle g \rangle = (S_{post} - S_{pre}) \,/\, (S_{max} - S_{pre}) \tag{2}$$

Differences between groups were tested with analysis of covariance (ANCOVA), using pretest scores as the covariate, after checking normality with the Shapiro–Wilk test, homogeneity of variance with

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Levene's test, and homogeneity of regression slopes (Field, 2018). Effect sizes are reported as partial eta squared and interpreted as small (.01), medium (.06), or large (.14) following Cohen (1988). Differences among the three environmental literacy subscales were examined with a MANCOVA followed by subscale-level ANCOVAs using a Bonferroni-adjusted α of .017. Because students were nested in intact classes within schools, the independence assumption may be violated; therefore, a two-level model (students within classes) was fitted as a robustness check, and intraclass correlations are reported.

3.6. Ethical Considerations

The study was approved by the Research Ethics Committee of Universitas Pelita Bangsa under approval number 045/KEPK-UPB/III/2026. Parents provided written informed consent, children gave verbal assent, and participants were told that they could withdraw at any time without consequence. Control classes received the EcoSci Kit after the posttest so that no group was permanently denied the intervention.

4. RESULTS AND DISCUSSION

4.1. Needs Analysis

The four participating schools held apparatus for only three of the eleven grade 5 science topics (27%). The waste audit identified PET bottles as the most abundant recyclable item (41% by count), followed by paper and cartons (28%), cans (12%), and bottle caps (10%). All eight interviewed teachers expressed willingness to use improvised media, but six named the absence of tested designs as their main barrier. These findings confirmed both the need for affordable apparatus and the availability of suitable raw materials.

4.2. Validity of the EcoSci Kit

Expert ratings indicated that the kit was valid on every aspect assessed, as shown in Table 3. All 20 items exceeded the criterion of 0.78, and the overall coefficient reached 0.90. The highest ratings were given for sustainability value and safety, whereas construction and durability received the lowest, though still valid, rating. Item-level Aiken's V values ranged from 0.83 to 0.94.

Table 3. Expert validation of the EcoSci Kit (six raters, 1–4 scale)

Aspect	Items	Aiken's V	Category
Content accuracy and curriculum fit	6	0.89	Valid
Construction and durability	5	0.86	Valid
Safety for children	4	0.92	Valid
Sustainability value	5	0.94	Valid
Overall	20	0.90	Valid

The experts requested three revisions: taping the edges of mirror pieces, enlarging the fonts on worksheets, and replacing single-layer cardboard in the circuit board with a double layer. All revisions were made before the trials began. Photographs of the five media before and after revision are shown in Figure

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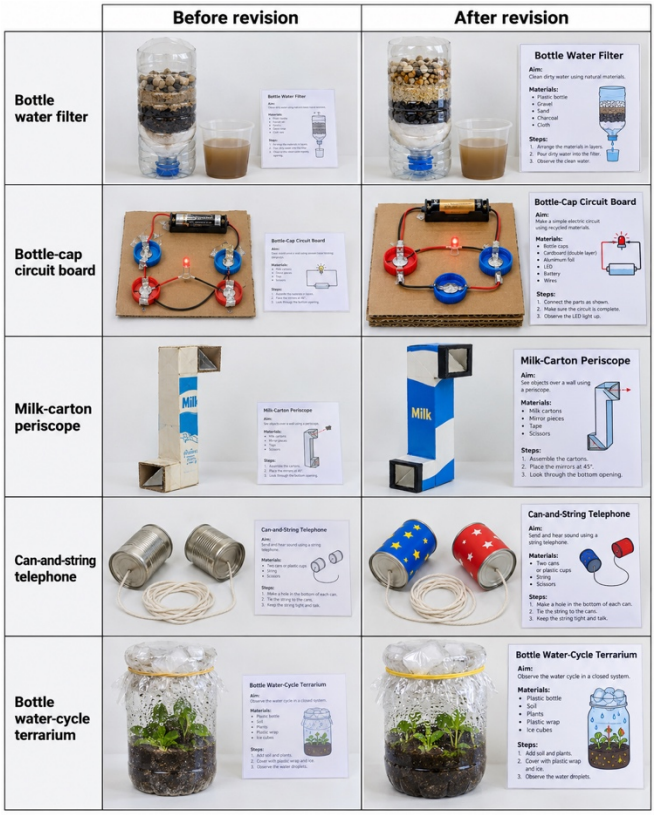


Figure 2. The five EcoSci Kit media before (left) and after (right) expert revision

4.3. Practicality of the EcoSci Kit

Both teachers and students judged the kit highly practical (Table 4). Teachers gave the highest rating to ease of assembly (93.8%) and the lowest to durability in storage (82.5%). In open responses, students most often reported that the activities were fun and that they wished to build a kit of their own at home. Because only four teachers took part, the teacher percentage should be read as indicative rather than conclusive. Teachers' open comments supported the ratings; one wrote, “the children were eager to bring bottles from home for the next lesson”, while a student commented, “I did not know a milk carton could show me things behind the wall”.

Table 4. Practicality ratings from the limited trial

Respondents	n	Mean score (%)	Category
Teachers	4	91.3	Highly practical
Students	32	88.6	Highly practical

4.4. Effect on Conceptual Understanding

The two groups began at an equivalent level, $t(120) = 0.39$, $p = .697$, but the experimental group finished well ahead (Table 5). Its normalised gain fell in the medium category, whereas that of the control group (0.30) lay exactly at the lower boundary of the medium category. The assumptions of ANCOVA

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were met: Shapiro–Wilk tests were non-significant for all cells ($p > .05$), Levene's test indicated equal variances, $F(1, 120) = 1.27$, $p = .262$, and the group × pretest interaction was non-significant, $F(1, 118) = 0.84$, $p = .361$. Controlling for pretest scores, ANCOVA revealed a large effect of the media, $F(1, 119) = 58.47$, $p < .001$, $\eta_p^2 = .33$, with adjusted posttest means of 72.3 for the experimental group and 58.6 for the control group. Because students were nested in classes, a two-level model was also fitted; the intraclass correlation was .08, and the treatment effect remained significant (b = 13.4, SE = 2.9, p = .004). This effect is larger than the effects typically reported for guided inquiry (Lazonder & Harmsen, 2016) whereas Indonesian recycled-media studies seldom report effect sizes, which prevents direct comparison (Wahyudi et al., 2024; Syahrial et al., 2026); the large effect may partly reflect the short intervention and novelty.

Table 5. Conceptual understanding scores (0–100)

Group	n	Pretest M (SD)	Posttest M (SD)	N-gain	Category
Experimental	62	41.2 (9.8)	72.6 (10.4)	0.53	Medium
Control	60	40.5 (10.1)	58.3 (11.2)	0.30	Medium (lower bound)

The experimental group answered both tiers correctly more often on every topic (Table 6). These are descriptive percentages without topic-level significance tests, so differences among topics should be read with caution. The difference was largest for light and reflection, where the periscope directly confronted the common belief that light travels from the eye to the object, and smallest for sound and the water cycle, topics in which the control group's demonstrations were already relatively concrete. An analysis of tier combinations at posttest showed that 12% of experimental and 21% of control students gave a correct answer with an incorrect reason (correct–incorrect), suggesting guessing or rote recall, while 6% and 5% gave an incorrect answer with a correct reason (incorrect–correct). The most persistent misconception in both groups was that light travels from the eye to the object.

Table 6. Percentage of students answering both tiers correctly at posttest, by topic

Topic	Experimental (%)	Control (%)	Difference (pp)
Separating mixtures	76	61	15
Electric circuits	70	55	15
Light and reflection	71	53	18
Sound through solids	75	63	12
Water cycle	71	59	12

4.5. Effect on Environmental Literacy

Environmental literacy also rose more in the experimental group (Table 7). Controlling for pretest scores, ANCOVA showed a large effect, F(1, 119) = 47.12, p < .001, ηp2 = .28. The adjusted posttest means were 3.92 for the experimental group and 3.41 for the control group, and the N-gains were 0.41 (medium) and 0.12 (low), respectively. The MANCOVA on the three subscales was significant (Pillai's trace = .34, p < .001). Subscale ANCOVAs with Bonferroni correction showed effects for knowledge (F = 14.62,

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$p < .001$, $\eta p^2 = .11$), attitude ($F = 52.37$, $p < .001$, $\eta p^2 = .31$), and intention ($F = 31.05$, $p < .001$, $\eta p^2 = .21$). Descriptively, the gap between groups was widest for attitude toward waste, followed by behavioural intention, and narrowest for environmental knowledge; these inferential results are consistent with the descriptive ranking.

Table 7. Environmental literacy scores (1–5 scale) and subscale gains

Group	Pretest M (SD)	Posttest M (SD)	Gain: knowledge	Gain: attitude	Gain: intention
Experimental	3.21 (0.48)	3.94 (0.41)	+0.58 (0.52)	+0.86 (0.61)	+0.75 (0.57)
Control	3.18 (0.50)	3.39 (0.46)	+0.24 (0.49)	+0.18 (0.55)	+0.21 (0.53)

4.6. Discussion

4.6.1. Valid and practical media at low cost

The EcoSci Kit met expert standards of validity while costing about six per cent of commercial apparatus. That the highest ratings went to safety and sustainability value is noteworthy, because these are precisely the grounds on which improvised equipment is usually questioned in elementary classrooms. The results suggest that careful design and explicit safety rules can answer such concerns. The comparatively lower rating for durability points to a practical trade-off: cardboard components wear out and need replacement. Rather than a weakness, this can become a recurring upcycling routine in which students rebuild parts of the kit, extending its educational value.

4.6.2. Why upcycled media improved conceptual understanding

Because both groups followed the same 5E lesson plans, the difference in gains can be attributed mainly to the media and the hands-on activity they enabled rather than to lesson structure, although class and teacher differences cannot be fully excluded in a quasi-experimental design. The finding is consistent with the ICAP framework, which predicts deeper learning when students move from passively watching to constructing and interacting (Chi & Wylie, 2014). Control students observed demonstrations, whereas experimental students built, tested, and argued about their own devices. The largest descriptive difference, on light and reflection, concerns a topic known for robust misconceptions (Vosniadou, 1994). When children saw an image appear through a periscope they had built themselves, the experience plausibly produced the dissatisfaction with prior ideas that conceptual change requires (Posner et al., 1982). The worksheets also mattered, because they kept the activity from becoming unstructured play, in line with evidence that inquiry works best with guidance (Kirschner et al., 2006; Lazonder & Harmsen, 2016; de Jong et al., 2023). The effect size is large and should be read with care, since novelty may have heightened engagement during a six-week intervention. Because comparable recycled-media studies seldom report effect sizes (Syahrial et al., 2026), the present estimate ($\eta p^2 = .33$) should be treated as a first benchmark that requires replication with longer interventions.

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4.6.3. Why upcycled media strengthened environmental literacy

Descriptively, the kit changed attitudes more than knowledge, a pattern that supports the view that direct, emotional, and material experience shapes children's environmental dispositions more powerfully than information alone (Sobel, 1996; Kollmuss & Agyeman, 2002; Chawla & Cushing, 2007). The pattern also mirrors recent Indonesian evidence that attitudes predict elementary students' recycling behaviour more strongly than knowledge does (Gunamantha & Dantes, 2025). The materials themselves carried a message that waste can become something valuable, functioning as a hidden curriculum, that is, the implicit values communicated by the learning environment rather than by explicit instruction (Jackson, 1968), that helps narrow the gap between ESD aspirations and classroom practice described by Stevenson (2007). Behavioural intention increased as well, but intention is not behaviour, and observed actions such as classroom waste sorting would provide stronger evidence. Taken together, the findings are consistent with a dual-pathway account in which a single set of media is associated with gains in both conceptual understanding and environmental affect, although the mediating pathways themselves were not tested, offering schools with tight budgets a validated alternative to commercial apparatus and offering teacher education a concrete means of integrating ESD into science methods courses.

5. CONCLUSION

This study set out to develop upcycled science learning media for elementary students and to examine their validity, practicality, and effectiveness. The resulting EcoSci Kit, built from household and school waste at a fraction of the cost of commercial apparatus, was judged valid by experts and highly practical by teachers and students. Compared with conventional instruction under identical lesson plans, it produced larger gains in grade 5 students' conceptual understanding and in their environmental literacy, with the strongest change in attitudes toward waste.

These findings carry practical and theoretical implications. Practically, elementary schools can adopt the kit as an affordable substitute for commercial apparatus, teacher education programmes can train pre-service teachers to design and validate upcycled media, and policymakers can link school waste management to the science curriculum as a single sustainability initiative. Theoretically, the study shows that one intervention can improve both conceptual understanding and environmental literacy, two outcomes that the literature usually examines separately. Whether these gains arise through the hypothesised cognitive and affective pathways remains to be tested with mediation analysis. For teachers, the cardboard parts of the circuit board and periscope should be checked after every two or three lessons and replaced as needed, mirror tape renewed, and kits stored dry in labelled boxes; students can rebuild worn parts as an upcycling routine.

Several limitations qualify these conclusions. The use of intact classes in a single district limits generalisability and may introduce selection bias and class or teacher effects, even though teachers rather than researchers delivered the lessons; the practicality trial involved only four teachers; the six-week duration did not allow novelty effects or long-term retention to be assessed, and environmental literacy

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relied on self-report. Future research should therefore employ cluster-randomised and multi-site designs, include delayed posttests, observe actual waste-related behaviour, and compare kits built by students with those built by teachers. Overall, the study shows that the waste surrounding under-resourced schools can, in the context of this study, be turned into a valid, practical, and effective resource for teaching science and sustainability together.

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Author Contributions

Bramianto Setiawan: Conceptualization, methodology, research design, supervision, data analysis, writing – original draft, and writing – review and editing. Septian Mukhlis: Investigation, development of learning media, data collection, implementation, and validation. Ahmad Fauzi: Methodology, statistical analysis, data interpretation, visualization, and writing – review and editing. All authors contributed to the development of the manuscript, critically reviewed its intellectual content, and approved the final version for publication.

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Ethics Statement

This study involved human participants and was approved by the Research Ethics Committee of Universitas Pelita Bangsa, Indonesia (approval number 045/KEPK-UPB/III/2026). The research was conducted in accordance with established ethical principles for educational research involving children. Written informed consent was obtained from the parents or legal guardians of all participating students, and verbal assent was obtained from the children before their participation. Participation was voluntary, and all participants were informed of their right to withdraw from the study at any time without consequences. The confidentiality and anonymity of participants were maintained throughout data collection, analysis, and reporting.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. To protect the privacy and confidentiality of the elementary school students involved in the research, individual-level data are not publicly available. Requests for access to anonymized research data

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may be directed to the corresponding author, subject to applicable ethical and institutional requirements.

Conflict of Interest Statement

The authors declare that they have no known financial or non-financial conflicts of interest that could have influenced the research, analysis, interpretation, or publication of this study.

Statement on the Use of Artificial Intelligence

The authors used Claude (Anthropic), a generative AI tool, to assist in drafting and language editing of this manuscript. All content was reviewed, verified, and revised by the authors, who take full responsibility for the final text.

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