ORIGINAL ARTICLE

The Effect of Project-Based Recycling Education on Students’ Recycling Knowledge Levels

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Abstract:

Background: Environmental education is important for developing sustainable behaviors and increasing recycling awareness among younger generations. However, traditional teaching methods may not be sufficient to improve students’ knowledge level and awareness regarding household waste and recycling.

Objective: This study aimed to examine the knowledge level and awareness of 7th-grade middle school students about household waste and recycling through project-based education.

Methods: A quasi-experimental design was used with two groups: an experimental group (n = 28) receiving project-based recycling education and a control group (n = 28) following the standard curriculum. An open-ended knowledge scale consisting of 13 questions was administered to both groups before and after the intervention. Data were analyzed using frequency tables and statistical tests to compare pre- and post-test results.

Results: The findings indicated that the knowledge level of the group receiving project-based recycling education increased, while there was no significant difference in the control group.

Conclusions: Project-based recycling education is more effective than traditional methods in increasing students’ knowledge about household waste and recycling. Based on these findings, it is recommended to incorporate projects and hands-on activities into the curriculum content.

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Introduction

RECYCLING is a core element of sustainable waste management and a priority competence for young learners. School-based programs that foreground active, hands-on tasks are more likely to move knowledge from general awareness to durable understanding. Within this instructional landscape, project-based learning (PBL) is particularly well suited because it situates concepts in real-life problems, requires inquiry and collaboration, and culminates in tangible products that consolidate learning (e.g., classroom projects on local waste categories and separation practices) (UNESCO, 2021; Blumenfeld et al., 1999; Yager, 2000).

In the national Science curriculum (MEB, 2018), the 7th-grade unit on Household Waste and Recycling provides a concrete context to develop such competencies. The outcomes emphasize distinguishing recyclable versus non-recyclable materials, planning feasible recycling projects, and paying systematic attention to waste control in students' immediate environment—targets that align naturally with a PBL approach. Traditional, teacher-centered instruction may introduce the topic but can offer limited opportunities for students to analyze waste streams, plan solutions, and apply newly learned concepts in authentic tasks, which are central to deepening understanding (MEB, 2018; UNESCO, 2021).

Against this backdrop, the present study examines whether a project-based recycling unit improves 7th-grade students' knowledge of household waste and recycling compared to the standard curriculum. The guiding question is: *What is the effect of project-based recycling education on the knowledge levels of 7th-grade students regarding household waste and recycling?* This focus narrows the contribution to a concrete learning outcome—knowledge—rather than broad environmental attitudes, and directly tests the added value of PBL in a routine curricular topic.

To address this question, we implemented a quasi-experimental pretest–posttest control-group design in two intact classes taught by the same teacher. The experimental class received project-based recycling education aligned with the curriculum, while the control class followed the standard sequence. Knowledge was assessed with an open-ended instrument administered before and after instruction; results were summarized with frequency tables and compared across groups and time points using appropriate inferential tests. The subsequent sections detail the method, report the findings, and discuss implications for integrating project-based activities into the recycling component of the 7th-grade Science curriculum.

Table 1. Learning Outcomes and Lesson Hours.

Learning Outcomes	Lesson Hour
Distinguishes between recyclable and non-recyclable materials in household waste.	2
Designs a project related to the recycling of household solid and liquid waste.	1
Questions recycling in terms of the effective use of resources.	1
Pays attention to waste control in their immediate environment.	1
Develops a project to deliver reusable items to those in need.	1

Methods

This research was conducted on the topic of "Household Waste and Recycling," which is included in the 5th section of the "Pure Substances and Mixtures" unit in the 7th grade science curriculum. The study was planned in accordance with the learning objectives and recommended lesson hours for the topic (**Table 1**), and was carried out over 6 lesson hours (MEB, 2018):

In the study, the "Knowledge Assessment Questions on Recycling" were administered as a pre-test to both the experimental and control groups. In the experimental group, the topic of "Household Waste and Recycling" was taught using the project-based learning method, while in the control group, traditional methods included in the 2018 Science Curriculum were used. The lessons in both groups were taught by the same teacher, thus controlling for the teacher effect.

A quasi-experimental design was used in the study. In quasi-experimental designs, two existing groups are selected and matched so that they have similar characteristics in terms of certain variables such as age, gender, and academic achievement level. This ensures that the groups are equivalent at the outset and makes the research results more reliable (Büyüköztürk et al., 2018). In this study, a pre-test–post-test control group quasi-experimental design model was applied. A pre-test was administered before the implementation, and a post-test was administered after the implementation. The students in the experimental group received lessons using the project-based learning method for 2.5 weeks. The same teacher followed the curriculum's learning plan with the students in the control group.

The projects and activities included in the study are aligned with the learning outcomes of the "Household Waste and Recycling" unit. These outcomes aimed to help students acquire knowledge and skills regarding the recycling of household waste and environmental awareness.

Participants

In the study, 7th grade students who had not previously received education on the content of the "Household Waste and Recycling" topic, which was planned as project-based, were included. Students in this age group possess the psychomotor skills necessary to carry out projects and designs. Two different classes were selected, with one designated as the control group and the other as the experimental group.

Out of the five classes available at the school, two were selected to have similar characteristics in terms of variables such as age, gender, and academic achievement. The 28 students in the experimental group received project-based recycling education, while the 28 students in the control group were taught using traditional methods from the curriculum.

Data Collection Tools

In order to measure the effectiveness of the trainings, an open-ended knowledge scale consisting of 13 questions was administered to both groups before and after the trainings. This scale was prepared by the researcher with expert opinions and its validity and reliability analyses were conducted.

A qualitative data collection tool was used in this study. The "Knowledge Assessment Questions on Recycling" were used as pre- and post-tests to collect data. The data obtained were analyzed to compare the changes in knowledge levels of the experimental and control groups. The answers to the open-ended questions were tabulated and expressed in terms of themes, codes, frequency, and total frequency.

The scores obtained by the students were analyzed using SPSS, and their pre-training knowledge levels and the frequencies of their responses were transferred into tables.

In order to ensure the reliability of the analysis of the responses, the opinions of two experts were obtained, and it was determined that the analyses were in agreement at a rate of 97%. Using expert opinions in reliability calculations is a common method to increase the accuracy of analyses (Yılmaz & Kaya, 2022; Demir, 2021; Kara & Arslan, 2023).

Ethics Committee Approval and Permission

For this research, ethics committee approval was obtained from Yıldız Technical University, and implementation permission was obtained from the Provincial Directorate of National Education.

Findings

Instrument and Scoring

Table 2. Pre-test FU counts by item and group (n = 28 per group).

Question #	Question	Fully Understood	
		Control	Experimental
1	What is household waste? Explain.	1	1
2	List the types of household waste.	0	0
3	Which of the household wastes are recyclable? List them.	0	0
4	Which types of household waste are non-recyclable? List them.	0	0
5	If you were to design a project related to the recycling of household solid and liquid waste, what would it be? Explain.	4	4
6	What are the benefits of recycling? Explain.	1	2
7	How do you relate the proper and efficient use of our resources to recycling? Explain.	2	0
8	What can be done to reduce waste? Explain.	2	1
9	What can be done to increase recycling in our immediate environment? Explain.	1	1
10	If you were to design a project to deliver surplus items to those in need, what would this project be like? Explain.	4	3
11	Imagine a recycling facility and illustrate your envisioned facility and its operation.	1	0
12	Draw the recycling symbols you know that appear on recyclable products and write their meanings next to them.	1	0
13	What do you know about the zero waste project? Explain.	0	1

The Knowledge Assessment Questions on Recycling (GDYBÖS) comprise 13 open-ended items. Responses were first coded as correct, non-original, incomplete/improvable, incorrect, blank, or irrelevant. For analysis, these were collapsed into three categories: Fully Understood (FU) for correct, Partially Understood (PU) for non-original/incomplete, and Not Understood (NU) for incorrect/blank/irrelevant.

Baseline (Pre-test) Equivalence

Pre-test distributions indicated limited prior knowledge in both groups, with notable NU concentrations for Q4 (non-recyclable types) and Q13 (zero-waste project). Mean pre-test scores did not differ significantly between groups (**Table 2**).

Pre-test distributions indicate that knowledge was largely clustered in PU/NU across items in both groups, evidencing limited prior mastery at baseline. The most pronounced gaps were on Q4 (non-recyclable household waste) and Q13 (Zero Waste project), where NU was high in both groups (Control NU = 23 and 22; Experimental NU = 26 and 14). Foundational concepts were also weak: Q2 and Q3 had no FU in either group, and Q1 yielded just one FU per group (with 26 PU and 1 NU in both). Small pockets of prior competence appeared on design-oriented items (e.g., Q5 FU = 4 in both groups; Q10 FU = 4 in Control and 3 in Experimental). Minor baseline asymmetries (e.g., Q7 FU: Control 2 vs Experimental 0; Q11 FU: 1 vs 0)

Table 3. Pre-Test Results of the Experimental and Control Groups and T-Test Analysis.

Group	Mean ± Standard Deviation	T-Test Value	P Value
Experimental Group (Pre-Test)	1.71 ± 0.15	-0.335	0.739
Control Group (Pre-Test)	1.73 ± 0.15		

were modest and occurred against an overall low FU profile, indicating broadly similar starting points.

The pre-test results of the experimental and control groups and the analysis results obtained using the independent samples t-test are presented in **Table 3**.

When the pre-test results were examined, the mean score of the experimental group on the "Knowledge Assessment Questions on Recycling" was found to be 1.71, while the mean score of the control group was 1.73. As a result of the independent samples t-test, the P value was found to be 0.739 ($P > 0.05$). This result indicates that there was no statistically significant difference between the pre-test scores of the experimental and control groups. This finding reveals that both groups had similar levels of knowledge about recycling and household waste before the training.

Tables 2 and **3** show the knowledge gaps of the experimental and control groups before the recycling education, as well as the areas in which they were similar or different.

Within-Group Change

Control Group (Curriculum-based Instruction)

Item-level FU counts changed little from pre- to post-test (**Table 4**, condensed). The paired-samples test confirmed no significant overall change (**Table 5**).

Table 4 summarizes item-level changes in the Fully Understood (FU) category for the control group from pre- to post-test and shows no systematic improvement under curriculum-based instruction. Across the 13 items, six remained unchanged (Q1, Q2, Q3, Q4, Q9, Q13), five declined (Q5, Q6, Q7, Q8, Q12), and only two showed marginal gains (Q10, Q11). The aggregate FU count decreased from 17 (pre) to 11 (post) ($\Delta = -6$), indicating a contraction in fully correct responses overall. Foundational knowledge items Q2–Q4 stayed at FU = 0 across both administrations, suggesting persistent gaps in listing and differentiating household waste types (recyclable vs. non-recyclable). Performance on design/application items was mixed: while Q10

Table 4. Control group FU counts by item (Pre → Post).

Question #	Question	Pre-Test	Post-Test	Δ
1	What is household waste? Explain.	1	1	0
2	List the types of household waste.	0	0	0
3	Which of the household wastes are recyclable? List them.	0	0	0
4	Which types of household waste are non-recyclable? List them.	0	0	0
5	If you were to design a project related to the recycling of household solid and liquid waste, what would it be? Explain.	4	1	-3
6	What are the benefits of recycling? Explain.	1	0	-1
7	How do you relate the proper and efficient use of our resources to recycling? Explain.	2	0	-2
8	What can be done to reduce waste? Explain.	2	1	-1
9	What can be done to increase recycling in our immediate environment? Explain.	1	1	0
10	If you were to design a project to deliver surplus items to those in need, what would this project be like? Explain.	4	5	1
11	Imagine a recycling facility and illustrate your envisioned facility and its operation.	1	2	1
12	Draw the recycling symbols you know that appear on recyclable products and write their meanings next to them.	1	0	-1
13	What do you know about the zero waste project? Explain.	0	0	0

Table 5. Control Group Pre-Test and Post-Test Results.

Group	Pre-Test (Mean ± SD)	Post-Test (Mean ± SD)	Difference (Mean ± SD)	r	Test Statistic	P Value
Control	1.73 ± 0.15	1.8 ± 0.22	0.07 (0.23)	0.258	-1.486	0.149

Table 6. Experimental group FU counts by item (Pre → Post).

Question #	Question	Pre Test	Post Test	Δ
1	What is household waste? Explain.	1	5	4
2	List the types of household waste.	0	7	7
3	Which of the household wastes are recyclable? List them.	0	12	12
4	Which types of household waste are non-recyclable? List them.	0	3	3
5	If you were to design a project related to the recycling of household solid and liquid waste, what would it be? Explain.	4	12	8
6	What are the benefits of recycling? Explain.	2	14	12
7	How do you relate the proper and efficient use of our resources to recycling? Explain.	0	19	19
8	What can be done to reduce waste? Explain.	1	11	10
9	What can be done to increase recycling in our immediate environment? Explain.	1	17	16
10	If you were to design a project to deliver surplus items to those in need, what would this project be like? Explain.	3	20	17
11	Imagine a recycling facility and illustrate your envisioned facility and its operation.	0	16	16
12	Draw the recycling symbols you know that appear on recyclable products and write their meanings next to them.	0	5	5
13	What do you know about the zero waste project? Explain.	1	19	18

Table 7. Analysis of the Difference Between the Pre-Test and Post-Test Results of the Experimental Group Participants.

	Median (min–max)	P*
Experimental Pre-Test	1.69 (1.46-2.08)	<0.001
Experimental Post-Test	2.46 (1.92-2.77)	

** It was analyzed using the Wilcoxon test.*

Table 8. Ranking Differences Between the Pre-Test and Post-Test Results of the Experimental Group.

Category	N	Mean Rank	Sum of Ranks
Negative Ranks (Post Test < Pre Test)	0[a]	0.00	0.00
Positive Ranks (Positive Test > Pre Test)	28[b]	14.50	406.00
Ties (Post Test = Pre Test)	0[c]		
Toplam	28		

a. Experimental Post-Test < Experimental Pre-Test
b. Experimental Post-Test > Experimental Pre-Test
c. Experimental Post-Test = Experimental Pre-Test

(surplus-items project) and Q11 (recycling facility) rose slightly (+1 each), Q5 (project design for solid/liquid waste) fell from 4 to 1. Coupled with small negative shifts on Q6–Q8 (benefits, resource efficiency link, waste-reduction actions), the pattern indicates that the standard curriculum did not translate into measurable gains in fully-correct, comprehensive responses for the control group. These descriptive results are consistent with the group’s non-significant pre–post difference reported elsewhere.

As a result, no statistically significant difference was found between the pre-test and post-test results of the control group (P = 0.149).

When the pre-test and post-test results of the control group were examined, the pre-test mean was found to be 1.73 ± 0.15, and the post-test mean was 1.8 ± 0.22. The difference between the means was calculated as -0.07 (± 0.23). As a result of the paired samples t-test, the p-value was found to be 0.149 ($p > 0.05$), and this difference was determined to be not statistically significant. These results indicate that there was no significant change between the pre- and post-test results in the control group.

Experimental Group (Project-based Instruction)

The experimental group showed a marked upward shift from pre- to post-test. FU counts increased across most items (**Table 6**). Median scores rose significantly (**Table 7**), and all students improved (**Table 8**).

Table 6 presents item-level changes in the FU category for the experimental group from pre- to post-test and shows uniform gains across all 13 items. Aggregated FU counts increased from 13 (pre) to 160 (post) (net +147 across items). Eight items exhibited large improvements (ΔFU ≥ 10)—namely Q3 (+12), Q6 (+12), Q7 (+19), Q8 (+10), Q9 (+16), Q10 (+17), Q11 (+16), Q13 (+18)—with post-test FU totals reaching 12, 14, 19, 11, 17, 20, 16, and 19, respectively. Three items showed moderate increases (Q2 +7; Q5 +8; Q12 +5), while two items posted smaller but positive shifts (Q1 +4; Q4 +3). In absolute post-test terms, the strongest FU concentrations were observed on Q7, Q9–Q11, and Q13 (16–20 FU), whereas Q4 (non-recyclable household wastes, FU = 3) and Q12 (recycling symbols, FU = 5) remained comparatively lower despite improvement. The pattern indicates broad, item-level advancement in fully correct responses within the experimental group, with the largest gains occurring on items tapping applied understanding and project/design tasks.

A statistically significant difference was found between the pre-test and post-test results of the experimental group students ($P < 0.001$). According to the results of the Wilcoxon test, all students' post-test scores were higher than their pre-test scores (Positive Ranks: 28, Negative Ranks: 0, Ties: 0). This indicates that the intervention had a positive effect on the students.

When the pre-test and post-test results of the experimental group students were compared, the median value for the pre-test was found to be 1.69 (min: 1.46 – max: 2.08), while the median value for the post-test was 2.46 (min: 1.92 – max: 2.77). As a result of the Wilcoxon test, a p value of <0.001 was obtained. Since the p value is less than 0.05, it was determined that there was a statistically significant difference between the pre-test and post-test results of the experimental group students.

The difference between the post-test and pre-test was found to be in favor of the post-test. As a result of the analysis, it was determined that all 28 students showed a positive trend in their test results (positive ranks: n = 28, mean rank: 14.50, sum of ranks: 406.00). No negative ranks or ties were observed. This indicates a significant improvement in the post-test results compared to the pre-test results.

Between-Group Post-test Comparison

Post-test FU counts favored the experimental group across all items (**Table 9**, condensed). The Mann–Whitney U test on post-test scores confirmed a significant between-group difference (**Table 10**).

Post-test FU counts show a pervasive advantage for the experimental group across items, with positive Δ on 12/13 items and parity only on Q2 (Δ = 0). The cumulative FU differential is +129 (sum of item-level Δs),

Table 9. Post-test FU counts by item and group, and Δ (Experimental – Control).

Question #	Question	Control	Experimental	Δ
1	What is household waste? Explain.	1	8	7
2	List the types of household waste.	22	22	0
3	Which of the household wastes are recyclable? List them.	18	20	2
4	Which types of household waste are non-recyclable? List them.	0	5	5
5	If you were to design a project related to the recycling of household solid and liquid waste, what would it be? Explain.	0	14	14
6	What are the benefits of recycling? Explain.	3	15	12
7	How do you relate the proper and efficient use of our resources to recycling? Explain.	0	16	16
8	What can be done to reduce waste? Explain.	1	12	11
9	What can be done to increase recycling in our immediate environment? Explain.	2	13	11
10	If you were to design a project to deliver surplus items to those in need, what would this project be like? Explain.	5	22	17
11	Imagine a recycling facility and illustrate your envisioned facility and its operation.	3	16	13
12	Draw the recycling symbols you know that appear on recyclable products and write their meanings next to them.	0	4	4
13	What do you know about the zero waste project? Explain.	0	17	17

Table 10. Comparison of the Post-Test Results of the Experimental and Control Groups.

Group	Median (Min–Max)*	Mean Rank	U Value	P Value
Experimental Group	2.46 (1.92 - 2.77)	41.43		
Control Group	1.85 (1.38 - 2.23)	15.57	30.000	<0.001

Analyzed using the Mann-Whitney U test.

reflecting a broad shift toward fully correct responses under project-based instruction. The largest margins occur on applied/project-oriented and explanatory prompts—Q10 (Δ = +17), Q13 (Δ = +17), Q7 (Δ = +16), Q11 (Δ = +13), Q5 (Δ = +14)—followed by consistent advantages on action/strategy items—Q8 (Δ = +11), Q9 (Δ = +11)—and benefits reasoning Q6 (Δ = +12). Foundational identification tasks show smaller or nil gaps: Q2 is saturated at FU = 22 in both groups (Δ = 0), while Q3 presents a modest edge (Δ = +2). Despite overall gains, domains that remained comparatively demanding still favor the experimental group—Q4: non-recyclable types (Δ = +5) and Q12: recycling symbols (Δ = +4)—indicating higher, but not maximal, post-test mastery relative to other items. On the basic definition item Q1, the experimental group retains a clear advantage (Δ = +7). In aggregate, **Table 9** evidences uniform, item-level superiority of the experimental group at post-test, most pronounced on tasks that require design, application, and integrated explanation.

A statistically significant difference was found between the post-test results of the experimental and control groups (P < 0.001). The median post-test score of the experimental group (2.46) was higher than that of the control group (1.85). According to the results of the Mann-Whitney U test, the mean rank of the experimental group (41.43) was significantly higher than that of the control group (15.57). This result indicates that the experimental group benefited more from the intervention.

When the post-test results were examined, the median value in the experimental group was 2.46 (min: 1.92 – max: 2.77) and the mean rank was 41.43. In the control group, the median value was 1.85 (min: 1.38 – max: 2.23) and the mean rank was 15.57. As a result of the Mann-Whitney U test, U = 30.000 and p < 0.001 were obtained. Since the p value is less than 0.05, it was determined that there was a statistically significant difference in the post-test results between the experimental and control groups.

Discussion and Conclusion

In this study, the knowledge levels regarding recycling and household waste of the experimental group, which received project-based recycling education, and the control group, which was taught using traditional methods, were compared. The findings showed that project-based learning is an effective method for increasing students' knowledge levels and creating environmental awareness. A significant increase in the knowledge levels of the experimental group was observed compared to the control group. This result is consistent with the findings of Kolodner et al. (2003), who reported that project-based learning increases students' knowledge levels and environmental awareness. It is also supported by the literature stating that project-based learning is effective in increasing knowledge levels on environmental issues (Coruhlu, 2017; Sugiyanto et al., 2020).

In the experimental group, the significant increase in the number of students in the "fully understood" category for basic questions such as "What is household waste?" and "What are the benefits of recycling?" demonstrated that project-based learning is effective in increasing students' knowledge levels about recycling and household waste. For example, in the experimental group, the number of students in the "fully understood" category for the question "What is household waste?" increased from 1 in the pre-test to 5 in the post-test. Similarly, for the question "List the types of household waste," there were no students in the "fully understood" category in the pre-test, but this number increased to 7 in the post-test. In the control group, however, no significant change was observed in these categories. These findings reveal that project-based learning is effective in understanding basic concepts.

A significant increase in the knowledge level of the experimental group was also observed in questions such as “Draw the recycling symbols you know that appear on recyclable products and write their meanings next to them” and “What do you know about the zero-waste project?” In particular, for the question “What do you know about the zero-waste project?”, the number of students in the “fully understood” category in the experimental group increased from 1 in the pre-test to 19 in the post-test. This demonstrates the effectiveness of project-based learning in raising awareness about recycling. In the control group, however, there was no significant change in the responses to these questions.

The SPSS analysis results also supported these findings. When the pre-test and post-test results of the experimental group were compared using the Wilcoxon test, a p value of < 0.001 was obtained. This result showed that there was a significant difference in favor of the post-test in the knowledge level of the experimental group. In addition, according to the results of the Mann-Whitney U test, a significant difference was found in favor of the experimental group between the post-test results of the experimental and control groups ($p < 0.001$). In the control group, however, according to the results of the paired samples t-test, no significant difference was found between the pre-test and post-test ($p = 0.149$). This indicates that traditional methods were insufficient in increasing the knowledge level.

As a result, project-based recycling education has been an effective method for increasing students’ knowledge levels about recycling and household waste. The post-test results of the experimental group showed that students improved both their theoretical knowledge and practical application skills. However, it was determined that there were still some deficiencies in certain areas, such as recycling symbols.

Limitations

Sample size and representativeness. The study involved two intact 7th-grade classes ($n = 28$ per group). This small, convenience sample from a single school limits statistical power and external validity, constraining generalization beyond similar grade levels, school types, and curricular settings.

Intervention duration and dosage. The project-based unit was implemented over a relatively brief instructional cycle. Without delayed post-tests, the stability and durability of knowledge gains remain unknown; effects may attenuate over time or vary with longer exposure.

Measurement scope. Outcomes focused on knowledge only (open-ended GDYBÖS items). The study does not speak to attitudes, intentions, or behaviors (e.g., actual recycling practices at school/home). Consequently, inferences are limited to cognitive gains, not to broader environmental literacy or behavior change.

Scoring subjectivity in open-ended responses. Although a common rubric (FU/PU/NU) and rater procedures were used, open-ended scoring entails residual subjectivity. Findings may be sensitive to rubric operationalization, especially on items with lower post-test mastery (e.g., Q4 non-recyclables; Q12 symbols). Reporting inter-rater statistics (e.g., percent agreement, Cohen's κ/weighted κ) helps contextualize this risk.

Design-related constraints. The quasi-experimental allocation of intact classes (rather than random assignment) leaves room for unmeasured group differences and classroom-level dependencies. Delivery by a single teacher reduces instructor variance but also limits generalizability to other teaching styles and implementation fidelities.

Item-level inference. Descriptive FU counts across 13 items illuminate where learning concentrated (e.g., Q7, Q9–Q11, Q13) and where challenges persisted (Q4, Q12), yet these itemwise contrasts were not adjusted for multiplicity. Thus, item-specific claims should be read as descriptive complements to the confirmatory pre–post and between-group tests.

Recommendations

Grounded in the quasi-experimental results (significant pre–post gains in the experimental group; Wilcoxon $p < .001$; and a significant post-test advantage over the control; $U = 30.000$, $p < .001$) and the item-level patterns (Tables 2, 6, 9), the following five recommendations are directly tied to the study's findings.

1. **Institutionalize PBL within the "Household Waste and Recycling" unit**. Sustain and scale the project formats that yielded the largest knowledge gains—items requiring application/design and integrated explanation (Q7, Q9–Q11, Q13 showed FU increases of +16 to +19). Embed these task types as core, not ancillary, components of the unit.
2. **Target the persistent gaps with focused, evidence-based instruction**. Two domains remained comparatively weak after intervention: non-recyclable household waste (Q4) and recycling symbols (Q12). Address these explicitly with contrastive examples (recyclable vs. non-recyclable look-alikes), concise visual exemplars for symbol–meaning mapping, and brief retrieval practice checks. This recommendation follows directly from the lower post-test FU on Q4 and Q12 despite overall gains.
3. **Sequence for foundation-then-project to leverage baseline deficits**. Pre-test profiles showed broadly limited prior knowledge (**Table 2**). Begin the unit with short, high-yield mini-lessons on definitions/classification (Q1–Q4, Q12), immediately followed by PBL cycles.

This sequencing aligns initial concept building with the project work that produced the strongest improvements.

4. **Use FU/PU/NU–aligned formative assessment to steer instruction**. Maintain the study's coding scheme operationally (FU/PU/NU) for quick, item-level checkpoints. Prioritize corrective feedback on items with low FU trajectories (especially Q4, Q12), and set explicit success criteria mirrored from the study's scoring (e.g., moving responses from PU→FU within each project milestone).
5. **Anchor materials and tasks in the local waste context to improve transfer**. Where mastery remained modest (e.g., Q4, Q12), curate context-specific artefacts (common local non-recyclables; locally used symbols/labels) and fold them into project deliverables (classification justifications, symbol glossaries attached to student projects). This directly targets the item types where students struggled while preserving the PBL formats that drove gains elsewhere.
6. **Scale and design**. Replicate with larger, multi-site samples and (where feasible) randomized or propensity-matched designs to strengthen causal inference and generalizability across schools and instructors.
7. **Longitudinal follow-ups**. Add delayed post-tests to examine retention and transfer, including whether knowledge gains translate into attitudinal shifts and observable
8. **Broadened outcome battery**. Complement open-ended knowledge with validated attitude/behavior measures and brief performance tasks targeting known pain points (Q4/Q12) to assess conceptual depth and symbolic literacy.
9. **Rubric transparency and reliability**. Publish a concise codebook with exemplars for FU/PU/NU, and report inter-rater reliability (e.g., κ, weighted κ with CIs) on a stratified subset; incorporate periodic drift checks to document scoring stability.
10. **Implementation fidelity and moderators**. Systematically track PBL fidelity (task features, student engagement time), and test moderators (prior achievement, classroom context) to identify for whom and under what conditions the approach yields the strongest gains.

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