Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Omani 10th Grade Students' Conceptual Understanding of Material Recycling and Environmental Waste Management

Asmahan AlKharusi
Sultan Qaboos University
Abdullah Ambusaidi
abdullah.ambusaidi@asu.edu.om
A'Sharqiyah University

Research Article

Keywords:

Posted Date: November 14th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11308846/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Omani 10th Grade Students' Conceptual Understanding of Material Recycling and Environmental Waste Management

Asmahan S. Alkharusi, PhD Student

Sultan Qaboos University
Muscat/Sultanate of Oman
http://orcid.org/0009-0008-4087-3435
Email: s125176@student.squ.edu.om

*Abdullah K. Ambusaidi, Professor
A 'Sharqiyah University
Ibra/Sultanate of Oman
http://orcid.org/0000-0003-1463-0209
Email: abdullah.ambusaidi@hasu.edu.om

* Corresponding Author

Abstract: This study examined Omani 10th grade students' conceptual understanding of material recycling and environmental waste management, including their ability to apply this understanding through design, explanation, interdisciplinary connections, and the incorporation of entrepreneurial features into proposed recycling solutions. A task-based assessment was administered to 453 students from eight schools in two educational governorates in the Sultanate of Oman. The instrument assessed three dimensions: design and drawing, description and interpretation, and linking ideas with different fields. Descriptive statistics and multivariate analysis of variance were used to examine students' performance and differences associated with gender and prior participation in environmental activities. Students demonstrated relatively strong performance in both description and interpretation and design and drawing, whereas their ability to link recycling ideas with different disciplinary fields was substantially weaker. Multivariate analyses indicated significant differences associated with gender, prior environmental-activity participation, and their interaction. Follow-up analyses showed gender differences in design and drawing and in linking ideas with different fields, while prior environmental-activity participation was associated only with linking ideas with different fields. Across the four recycling tasks, the proportion of students demonstrating innovative entrepreneurial features ranged from 41.8% to 62.7%, indicating variation across task contexts. The findings highlight the value of connecting recycling concepts with authentic design tasks, interdisciplinary learning, and environmental entrepreneurship. The study recommends strengthening practical, context-based sustainability learning and supporting teachers in integrating such experiences into school science and environmental education.

Keywords recycling education · environmental waste · conceptual understanding · environmental entrepreneurship · sustainability education

1 Introduction

Recycling is an important component of sustainable resource management because it enables materials that would otherwise become waste to be recovered and returned to productive use. Within a circular-economy perspective, recycling can contribute to broader efforts to reduce environmental pressures and support more sustainable patterns of resource use (Abbas et al. 2025). However, recycling is not simply a waste-management procedure; understanding and addressing recycling-related problems may require students to draw on scientific knowledge, technological processes, design considerations, and broader environmental and social perspectives.

In educational contexts, conceptual understanding of recycling extends beyond recognizing recyclable materials or recalling definitions. It involves understanding how materials can be recovered, transformed, and returned to use, as well as applying this knowledge when considering possible responses to waste-related problems. Evidence suggests that students may hold partial or restricted conceptions of recycling (Çoruhlu and Nas 2018; Şeker 2023; Laius et al. 2024; Türksoy and Altıntaş 2025). Recent evidence from secondary education further indicates that students' understanding of recycling and the circular economy may not develop to the same extent as their sustainability-related attitudes and willingness to act (Laius et al. 2024). For example, Çoruhlu and Nas (2018) found that many primary-school students initially associated recycling predominantly with waste paper and were unable to provide a comprehensive explanation of the concept. Such findings indicate that familiarity with recycling does not necessarily imply a well-developed conceptual understanding. Meaningful assessment may therefore require students to demonstrate how they use their knowledge in context, for example by explaining recycling processes, representing possible solutions, and considering whether proposed solutions are appropriate to a particular waste problem. This broader perspective is especially relevant when recycling is approached as an interdisciplinary sustainability issue rather than as an isolated environmental concept.

This multidimensional nature of recycling makes it particularly relevant to education for sustainable development (ESD), which emphasizes learning that enables individuals to understand interconnected sustainability challenges and contribute to informed and responsible action (UNESCO 2020). In school contexts, recycling can therefore provide an applied setting in which students move beyond recalling environmental information to explaining problems, representing possible solutions, and connecting their ideas across different fields. Such learning is particularly important when environmental education is intended not only to increase awareness but also to develop students' capacity to respond to sustainability challenges through meaningful and context-based learning experiences.

Recycling also provides a useful context for interdisciplinary and design-oriented learning because addressing waste-related problems often requires students to draw on more than one disciplinary perspective. Recent work on integrating circular-economy principles into STEM education similarly emphasizes the value of real-world, problem-oriented contexts for connecting disciplinary knowledge and developing solutions to sustainability challenges (Nguyen 2023). Tan and So (2019), for example, found that contextual environmental learning supported Grade 8 students in activating prior knowledge and developing interdisciplinary connections across science, geography, and history. More recently, Karakuyu and Karafil (2026) reported significant pre–post improvements in secondary school students' design thinking, recycling-related behaviours, and STEAM attitudes following participation in recycling-based STEM activities. Related work at the secondary-school level has also highlighted the value of hands-on sustainability projects that combine recycling and circular-economy concepts

with product development, critical thinking, problem solving, and interdisciplinary learning (Jäggle et al. 2024). Their qualitative findings also indicated that students perceived gains in problem solving, creativity, collaboration, and understanding of interdisciplinary STEM connections. Taken together, these findings suggest that recycling-related tasks can provide a meaningful setting in which students not only demonstrate environmental knowledge but also connect disciplinary perspectives and use design-oriented thinking to develop responses to environmental problems.

Despite the growing emphasis on environmental education, the ways in which environmental issues are addressed in schools vary considerably. A recent systematic review of environmental education teaching practices identified increasing attention to approaches such as cross-disciplinary integration, outdoor learning, participatory learning, and critical thinking in school-based environmental education. At the same time, the review highlighted continuing limitations in teaching practices, reinforcing the need for more interdisciplinary and context-responsive approaches (Zhang et al. 2025). Applied environmental activities can provide opportunities for students to engage with sustainability problems in meaningful contexts rather than encountering environmental concepts only as abstract knowledge. When such experiences are deliberately connected to curricular learning, they may support students in drawing relationships among different forms of knowledge and in considering possible responses to authentic environmental problems. This orientation is consistent with Education for Sustainable Development, which emphasizes learning that enables students to engage actively with interconnected sustainability challenges (UNESCO 2020). Beyond developing environmental understanding, sustainability education can also provide opportunities for students to consider how environmental problems may be addressed through innovative and economically viable solutions. Entrepreneurship is widely recognized as an important element in supporting sustainable economic and social development.

Within educational contexts, connecting entrepreneurship with sustainability can extend environmental learning from recognizing problems to considering solutions that combine environmental value with practical and social relevance. Environmental entrepreneurship is particularly pertinent in this respect because it positions environmental challenges as contexts in which learners can identify opportunities, develop ideas, and consider how those ideas might be translated into environmentally responsible initiatives. Evidence from the Omani school context supports the educational relevance of this connection. Ambusaidi et al. (2024), in a quasi-experimental study involving 134 Omani Grade 8 students, found that a sustainable environmental tourism education programme significantly improved students' inclination to engage in entrepreneurship related to sustainable environmental tourism. Although entrepreneurial inclination differs from demonstrated entrepreneurial performance, the study provides evidence that entrepreneurship can be meaningfully incorporated into environmental and sustainability education for Omani school students. This perspective is consistent with the broader aims of Education for Sustainable Development, which emphasize empowering learners to contribute to more sustainable societies through informed and responsible action (UNESCO 2020).

Taken together, previous research suggests that recycling education can address several complementary aspects of student learning, ranging from conceptual understanding to applied problem solving, design thinking, and interdisciplinary connections. However, these aspects have often been examined separately or within specific instructional interventions. Consequently, less is known about how students demonstrate these dimensions simultaneously when they are required to respond independently to authentic recycling and waste-management

problems. This distinction is important because students may be able to explain or visually represent a recycling idea without necessarily being able to connect that idea to broader scientific, technological, environmental, mathematical, or entrepreneurial considerations.

A similar gap can be observed in the Omani context. For example, Ambusaidi and Al Fulaiti (2022) examined the effects of an environmental education programme on fourth-grade students' knowledge, attitudes, and behaviours toward waste management, while Al Balushi and Ambusaidi (2023) investigated Omani secondary school students' self-reported environmental attitudes and behaviours and the school-related factors associated with them. These studies provide important evidence on environmental education in Oman; however, comparatively less attention has been given to how secondary school students demonstrate and apply their recycling-related understanding when responding to authentic waste-management problems that require them to explain their ideas, represent possible solutions through design, and connect those solutions across different disciplinary fields and entrepreneurial considerations.

Accordingly, the present study examines Omani Grade 10 students' conceptual understanding of material recycling and environmental waste management through a task-based assessment that requires students to apply their understanding to authentic recycling-related problems. Particular attention is given to their ability to represent and explain proposed solutions, connect their ideas across disciplinary fields, and incorporate entrepreneurial considerations. It also examines differences in students' performance according to gender and prior participation in environmental activities. The study addresses the following research questions:

1.1 Research questions

RQ1: What is the level of conceptual understanding of Omani 10th grade students regarding material recycling and environmental waste management?

RQ2: Are there statistically significant differences in Omani 10th grade students' conceptual understanding of material recycling and environmental waste management according to gender, prior participation in environmental activities, and the interaction between these variables?

RQ3: To what extent do Omani 10th grade students demonstrate entrepreneurial features in their proposed solutions to material recycling and environmental waste-management problems?

2 Methodology

2.1 Study design

The present study employed a cross-sectional descriptive-comparative quantitative design to examine Grade 10 students' conceptual understanding of material recycling and environmental waste management. Students' performance was assessed using a task-based assessment, and differences in the three assessment dimensions were examined according to gender and prior participation in environmental activities. As the study involved no experimental manipulation or intervention, the analyses were intended to describe patterns of performance and examine associations between the study variables rather than establish causal relationships.

2.2 Participants and sampling

The study included 453 10th grade students selected from eight schools located in two educational governorates in the Sultanate of Oman during the second semester of the 2024/2025 academic year. The schools were selected purposively based on their accessibility and willingness to participate in the study. Grade 10 was selected because it represents the final year before students enter Grades 11–12 in the Omani education system, a stage at which students are expected to have developed foundational scientific knowledge relevant to environmental and sustainability-related issues. The sample included students with varying levels of academic achievement. Table 1 presents the distribution of participants according to gender and prior participation in environmental activities.

Table 1. Distribution of the Study Sample

Variable	Male	Female	Total
Participated in Prior Environmental Activities	41	44	85
Not Participated in Prior Environmental Activities	211	157	368
Total	252	201	453

2.3 Study instrument

The study employed a task-based assessment designed to examine Grade 10 students' conceptual understanding of material recycling and environmental waste management and their ability to apply this understanding to recycling-related problems. The assessment consisted of four challenge-based tasks focusing on car tires, wood waste, grey water, and palm tree waste. Each task required students to propose and represent a recycling or reuse solution and explain how their proposed idea addressed the environmental problem presented.

Students' responses were assessed across three dimensions: (1) Design and Drawing, which addressed the clarity and creativity of the idea, innovation in design, accuracy of drawing details, and relevance of the design to the problem; (2) Description and Interpretation, which addressed the accuracy of the description, the relationship between the description and the proposed design, and practical feasibility; and (3) Linking Ideas with Different Fields, which was scored using six criteria: science, entrepreneurship, sustainability, technology, geography, and mathematics. The assessment tasks were developed to reflect applied recycling and waste-management problems relevant to students' educational and local contexts (Figure 1). The selection and formulation of the tasks were informed by the study objectives and relevant literature on recycling, sustainability, and education for sustainable

development, while considering their appropriateness for the age and educational level of the participants (UNESCO 2020).

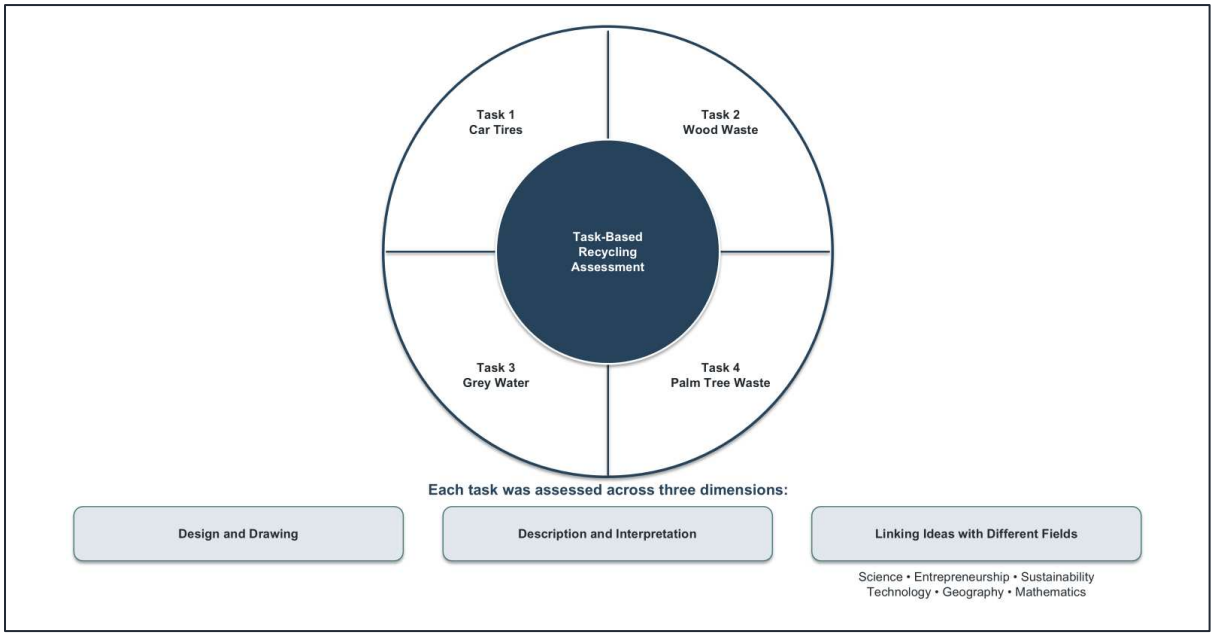


Fig. 1 Structure of the task-based recycling assessment

The content validity of the assessment was examined by a panel of eight experts specializing in ESD, environmental education, and science education from universities and the Ministry of Education. The panel included faculty members, teachers, and educational supervisors who reviewed the relevance and appropriateness of the assessment tasks and scoring criteria in relation to the study objectives. Their feedback and suggestions were considered, and several aspects of the assessment were revised accordingly. As evidence related to the internal structure of the assessment, the relationships between the three assessment dimensions and the overall assessment score were examined using Pearson correlation coefficients. The correlations between the dimension scores and the total assessment score ranged from .77 to .90, indicating strong positive associations between performance on each dimension and overall performance on the assessment.

To support consistent scoring of students' responses, an analytic scoring rubric was developed for the task-based assessment (Table 2). The use of explicit performance descriptors in analytic rubrics can enhance transparency and consistency in performance assessment and facilitate the differentiation of levels of student performance (Brookhart 2013; Jönsson and Svingby 2007).

Table 2. Analytic Scoring Rubric for the Task-Based Assessment

Dimension	Criterion	Max Score	Detailed Scoring			
Design and Drawing (35 points)	Clarity and Creativity of Idea	10	Innovative (10)	Conventional (7)	Unclear (3)	Absent (0)
	Innovation in Design	10	Highly Innovative (10)	Moderately Innovative (7)	Weak Innovation (3)	Not Innovative (0)

	Accuracy of Drawing Details	10	Accurate and Consistent (10)	Mostly Accurate (7)	Some Details Clear (3)	Details Absent (0)
	Relevance of Design to the Problem	5	Direct and Relevant (5)	Partial Relevance (3)	Weak Relevance (1)	Not Applied (0)
Description and Interpretation (30 points)	Accuracy of Description	10	Comprehensive and Accurate (10)	Good but Incomplete (7)	Incomplete /Unclear (3)	No Description (0)
	Clarity of Link between Description and Design	10	Clear and Logical (10)	Moderately Clear (7)	Weak Link (3)	Absent (0)
	Practical Feasibility	10	Practically Feasible (10)	Feasible with Challenges (7)	Major Difficulty (3)	Not Feasible (0)
Linking the Idea with Different Fields (35 points)	Science	7	Strong Link (7)	Good Link (5)	Weak Link (1)	Absent (0)
	Entrepreneurship	7	Innovative Entrepreneurial Approach (7)	Moderate Approach (5)	Weak Approach (1)	Absent (0)
	Sustainability	7	Strong Contribution to Sustainability (7)	Clear Contribution to Sustainability (5)	Limited Contribution to Sustainability (1)	No Evident Contribution to Sustainability (0)
	Technology	7	Innovative Use of Technology (7)	Good Use (5)	Weak Use (1)	Absent (0)
	Geography	4	Clear Link (4)	Partial Link (2)	Weak Use (1)	Not Applied (0)
	Mathematics	3	Innovative Mathematical Use (3)	Moderate Use (2)	Weak Use (1)	Not Applied (0)
Total		**100**				

To examine inter-rater agreement, the responses of 30 students were independently scored by the first author and a second assessor with comparable teaching experience using the analytic scoring rubric. Agreement between the two raters was examined using Cohen's kappa, which yielded $\kappa = .88$, indicating a strong level of agreement (McHugh 2012). The assessment was administered to the main sample after obtaining official permission from the Ministry of Education (approval no. 2825561976). It was completed over two consecutive 40-minute class sessions, for a total administration time of approximately 80 minutes.

2.4 Data analysis

Students' responses were scored using the assessment rubric presented in Table 2. Each criterion was assigned a set of predefined performance levels with corresponding numerical scores, with the maximum score varying

according to the criterion. The three dimensions had maximum scores of 35 points for Design and Drawing, 30 points for Description and Interpretation, and 35 points for Linking Ideas with Different Fields, yielding a maximum total assessment score of 100 points. One student did not complete Tasks 3 and 4. In the scoring dataset used for the primary analyses, non-completed tasks were assigned a score of zero and retained in the four-task scoring framework. Accordingly, dimension and total scores were averaged across all four tasks for all 453 students. These averaged scores were used in the subsequent statistical analyses. For the task-specific entrepreneurship analysis, however, percentages were calculated using only valid responses to each task. The descriptive indicators associated with each scoring level were used to guide the evaluation of students' responses consistently across the four recycling tasks. After coding the scores, the data were entered into SPSS (Version 22) for descriptive and inferential statistical analyses, including the calculation of means, standard deviations, and multivariate analysis of variance (MANOVA). The results were interpreted in light of the research questions.

Prior to the multivariate analysis, relevant MANOVA assumptions were examined. Box's M test indicated heterogeneity of the variance–covariance matrices across the gender-by-participation groups, and Levene's tests indicated unequal variances for two of the three dependent variables. Pillai's Trace was therefore used as the primary multivariate test because of its greater robustness to violations of homogeneity assumptions. Potential multivariate outliers were examined using Mahalanobis distance; a small number of cases exceeded the conservative $p < .001$ criterion. A sensitivity analysis excluding these cases produced the same pattern of statistical significance, and all cases were therefore retained in the primary analysis. For statistically significant multivariate effects, follow-up univariate tests were examined to identify the assessment dimensions contributing to the overall effect. Partial eta squared (ηp^2) was calculated as an effect-size measure for the univariate effects. Given the evidence of heterogeneity of variance for two dependent variables, the follow-up univariate results were additionally examined using heteroscedasticity-robust (HC3) standard errors as a sensitivity analysis.

For the third research question, performance on the Entrepreneurship criterion was examined separately for each of the four recycling tasks. Because the analytic rubric defined four discrete performance levels for this criterion—Absent (0), Weak Approach (1), Moderate Approach (5), and Innovative Entrepreneurial Approach (7)—frequencies and percentages were calculated for each level within each task. The task-level distributions were retained rather than combining scores across tasks into a new overall classification, as the rubric did not specify cut-off scores for classifying an aggregated entrepreneurship score.

3 Results

The results are presented according to the sequence of the research questions.

3.1 RQ (1): What is the level of conceptual understanding of Omani 10th grade students regarding material recycling and environmental waste management?

To answer this question, means and standard deviations were calculated for the three main dimensions of the assessment (Table 3).

Table 3. Means (M) and Standard Deviations (SD) for the Three Assessment Dimensions

Dimension	Total Score	*M*	*SD*
Design and Drawing	35	27.13	9.43

Description and Interpretation	30	23.58	8.04
Linking Ideas with Different Fields	35	12.38	8.79

As shown in Table 3, students demonstrated comparatively higher performance in Description and Interpretation and Design and Drawing dimensions, achieving approximately 78.6% and 77.5% of the maximum possible scores, respectively. In contrast, performance in Linking Ideas with Different Fields was substantially lower, with students achieving approximately 35.4% of the maximum possible score. These results indicate that students were more successful in describing, interpreting, and visually representing their recycling ideas than in connecting those ideas across different disciplinary fields.

3.2 RQ (2): Are there statistically significant differences in Omani 10th grade students' conceptual understanding of material recycling and environmental waste management according to gender, prior participation in environmental activities, and the interaction between these variables?

To address this question, means and standard deviations were calculated for the three assessment dimensions according to gender and prior participation in environmental activities, as presented in Table 4.

Table 4. *Means and Standard Deviations by Gender and Prior Participation in Environmental Activities*

Dimension	Gender	Participation in Prior Environmental Activities	*M*	*SD*
Design and Drawing	Male	No	26.22	10.14
	Male	Yes	25.35	10.05
	Female	No	28.20	8.62
	Female	Yes	29.28	7.26
Description and Interpretation	Male	No	22.96	8.55
	Male	Yes	24.32	5.96
	Female	No	24.04	7.75
	Female	Yes	24.24	8.20
Linking Ideas with Different Fields	Male	No	13.86	9.39
	Male	Yes	17.96	10.74
	Female	No	9.49	6.60
	Female	Yes	10.40	6.41

Table 4 shows descriptive variations in students' scores across the three dimensions according to gender and prior participation in environmental activities. For Design and Drawing, females had higher mean scores than males in both the non-participant and participant groups. Scores for Description and Interpretation were relatively similar across the four groups, although male participants showed a somewhat higher mean than male non-participants. A different pattern was observed for Linking Ideas with Different Fields, where males had higher mean scores than females, particularly among students who had previously participated in environmental activities. These descriptive differences were subsequently examined using multivariate analysis of variance (MANOVA) to

determine whether students' combined performance across the three assessment dimensions differed significantly according to gender, prior environmental-activity participation, and their interaction. Pillai's Trace was used as the primary multivariate statistic, as presented in Table 5.

Table 5. Multivariate Effects Based on Pillai's Trace

Source of Variation	Pillai's Trace	F-value	Hypothesis df	Error df	p-value
Gender	0.144	25.06	3	447	< .001
Participation in Prior Environmental Activities	0.018	2.69	3	447	.046
Gender × Participation in Prior Environmental Activities	0.020	3.11	3	447	.026

As shown in Table 5, statistically significant multivariate differences in the combined assessment dimensions were found according to gender, Pillai's Trace = .144, $F(3, 447) = 25.06$, $p < .001$, and prior participation in environmental activities, Pillai's Trace = .018, $F(3, 447) = 2.69$, $p = .046$. The gender × prior-participation interaction was also statistically significant at the multivariate level, Pillai's Trace = .020, $F(3, 447) = 3.11$, $p = .026$. Follow-up univariate tests were therefore examined to identify the assessment dimensions contributing to these multivariate differences (Table 6).

Table 6. Follow-up Univariate Tests Across the Three Assessment Dimensions

Source of Variation	Dimension	Sum of Squares	df	Mean Square	F	p	Partial η^2
Gender	Design and Drawing	598.938	1	598.938	6.810	.009	0.015
	Description and Interpretation	17.175	1	17.175	0.266	.607	0.001
	Linking Ideas with Different Fields	2444.987	1	2444.987	34.628	< .001	0.072
Prior Environmental Activities	Design and Drawing	0.745	1	0.745	0.008	.927	< .001
	Description and Interpretation	42.673	1	42.673	0.660	.417	0.001
	Linking Ideas with Different Fields	430.827	1	430.827	6.102	.014	0.013
Gender × Prior Environmental Activities	Design and Drawing	64.910	1	64.910	0.738	.391	0.002
	Description and Interpretation	23.019	1	23.019	0.356	.551	0.001
	Linking Ideas with Different Fields	173.264	1	173.264	2.454	.118	0.005

Error	Design and Drawing	39487.245	449	87.945	—	—
	Description and Interpretation	29042.806	449	64.683	—	—
	Linking Ideas with Different Fields	31702.265	449	70.606	—	—

The follow-up univariate tests showed statistically significant gender differences in Design and Drawing, $F(1, 449) = 6.81$, $p = .009$, $\eta p^2 = .015$, and Linking Ideas with Different Fields, $F(1, 449) = 34.63$, $p < .001$, $\eta p^2 = .072$. No statistically significant gender difference was found for Description and Interpretation, $F(1, 449) = 0.27$, $p = .607$, $\eta p^2 = .001$. As indicated by the descriptive means in Table 4, female students obtained higher scores than male students in Design and Drawing, whereas male students obtained higher scores in Linking Ideas with Different Fields.

For prior participation in environmental activities, no statistically significant difference was found in Design and Drawing, $F(1, 449) = 0.01$, $p = .927$, $\eta p^2 < .001$, or Description and Interpretation, $F(1, 449) = 0.66$, $p = .417$, $\eta p^2 = .001$. A statistically significant difference was found, however, in Linking Ideas with Different Fields, $F(1, 449) = 6.10$, $p = .014$, $\eta p^2 = .013$. As shown by the descriptive means in Table 4, students who had previously participated in environmental activities obtained higher scores on this dimension.

Although the overall multivariate interaction between gender and prior participation in environmental activities was statistically significant (Table 5), none of the follow-up univariate interaction effects reached statistical significance: Design and Drawing, $F(1, 449) = 0.74$, $p = .391$, $\eta p^2 = .002$; Description and Interpretation, $F(1, 449) = 0.36$, $p = .551$, $\eta p^2 = .001$; and Linking Ideas with Different Fields, $F(1, 449) = 2.45$, $p = .118$, $\eta p^2 = .005$. Accordingly, the multivariate interaction should be interpreted as reflecting a combined pattern across the three dimensions rather than a statistically significant interaction within any single dimension. The HC3-robust sensitivity analyses yielded the same pattern of statistical significance as the conventional univariate tests, supporting the robustness of the reported conclusions.

3.3 RQ (3): To what extent do Omani 10th grade students demonstrate entrepreneurial features in their proposed solutions to material recycling and environmental waste-management problems?

To address this research question, students' performance on the Entrepreneurship criterion was examined separately across the four recycling tasks using the four performance levels specified in the analytic scoring rubric. As shown in Table 7, the proportion of students demonstrating Innovative Entrepreneurial Features varied across tasks, ranging from 41.8% to 62.7%. Innovative Entrepreneurial Features were most frequent in Task 2 (62.7%) and Task 1 (62.0%), compared with 48.0% in Task 4 and 41.8% in Task 3. Conversely, the proportion showing No Entrepreneurial Features was higher in Tasks 3 (42.5%) and 4 (39.4%) than in Tasks 1 (17.0%) and 2 (21.2%). Weak and Moderate Entrepreneurial Features accounted for comparatively smaller proportions across all four tasks. Overall, the findings indicate that entrepreneurial features were evident in students' recycling proposals, but their level varied across the different recycling tasks.

Table 7. Distribution of Entrepreneurship Performance Levels Across the Four Recycling Tasks

Entrepreneurship performance level	Task 1 n (%)	Task 2 n (%)	Task 3 n (%)	Task 4 n (%)
No Entrepreneurial Features (0)	77 (17.0)	96 (21.2)	192 (42.5)	178 (39.4)
Weak Entrepreneurial Features (1)	36 (7.9)	25 (5.5)	26 (5.8)	20 (4.4)
Moderate Entrepreneurial Features (5)	59 (13.0)	48 (10.6)	45 (10.0)	37 (8.2)
Innovative Entrepreneurial Features (7)	281 (62.0)	284 (62.7)	189 (41.8)	217 (48.0)
Valid N	453	453	452	452

Note. Percentages were calculated using the number of valid responses for each task. One student did not complete Tasks 3 and 4.

4 Discussion

The findings related to the first research question showed relatively strong and closely comparable performance in Description and Interpretation and Design and Drawing, with students achieving 78.6% and 77.5% of the maximum possible scores, respectively. This pattern indicates that many students were able to express their recycling-related understanding through explanations and visual representations of possible solutions. Because the assessment required students to respond to concrete waste-related challenges, the relatively strong performance on these two dimensions may reflect their ability to apply familiar environmental knowledge when the problem was presented in a tangible and solution-oriented form. Design-based learning research similarly shows that authentic design projects can engage students in developing, documenting, and representing solutions through a structured design process (Doppelt 2009). The present findings extend this perspective to recycling-related assessment by showing that, even in the absence of a preceding instructional intervention, many students were able to generate, represent, and explain responses to authentic waste-management problems.

In contrast, Linking Ideas with Different Fields showed substantially weaker performance, with students achieving only 35.4% of the maximum possible score. The size of this difference is noteworthy because it suggests that being able to generate, describe, or visually represent a recycling solution does not necessarily mean that students can explain that solution through multiple disciplinary perspectives. Linking a single recycling idea to science, technology, mathematics, geography, sustainability, and entrepreneurship requires students not only to possess relevant knowledge within these domains but also to recognize relationships among them and mobilize that knowledge in response to a common problem. Interdisciplinary integration may therefore represent a more demanding form of performance than description or visual representation. This interpretation is consistent with Tan and So (2019), who showed that interdisciplinary thinking involves the activation and coordination of different knowledge resources and that contextual environmental experiences can support students in constructing connections across disciplinary boundaries. A similar pattern has been reported in teacher education, where Santiani et al. (2024) found that interdisciplinary science learning supported prospective teachers' interdisciplinary thinking and environmental literacy. From this perspective, the relatively low score observed in the present study should not necessarily be interpreted as a general lack of recycling knowledge. Rather, it may indicate a specific difficulty in integrating and applying knowledge across disciplinary boundaries when

responding to a complex environmental problem. This distinction is important because sustainability problems such as waste management rarely belong to a single disciplinary domain and often require scientific understanding to be considered alongside technological, social, economic, and environmental dimensions.



Fig. 2 Examples of students' proposed recycling and reuse solutions across the assessment tasks. The examples are presented for illustrative purposes and do not represent the overall level of performance in the sample.

The examples presented in Figure 2 illustrate how some students translated recycling ideas into proposed product designs. The proposed solutions, including structures made from recycled wood, toys produced from used tires, mobile food-related designs, and household items made from discarded materials, demonstrate the variety of solutions generated in response to the assessment tasks. These examples complement the quantitative findings for Design and Drawing by illustrating the types of visual and product-oriented responses represented in students' work. At the same time, they should be interpreted as illustrative examples rather than as evidence of the overall level of conceptual understanding across the sample.

The findings related to the second research question revealed a differentiated pattern of gender-related differences across the three assessment dimensions. Female students obtained significantly higher scores in Design and Drawing, whereas male students obtained significantly higher scores in Linking Ideas with Different Fields; no statistically significant gender difference was found in Description and Interpretation. Importantly, these differences were not uniform in magnitude. The magnitude of the gender-related difference was relatively small for Design and Drawing ($\eta p^2 = .015$) but more pronounced for Linking Ideas with Different Fields ($\eta p^2 = .072$), suggesting that the clearest gender-related difference in the present assessment concerned students' ability to connect their recycling ideas across disciplinary domains. The absence of a gender difference in Description and

Interpretation further indicates that gender was not consistently associated with recycling-related performance across the assessment as a whole. Rather than implying inherent differences in ability, this dimension-specific pattern may reflect differences in prior experiences, opportunities for engagement, familiarity with particular forms of task performance, or other contextual factors that were not measured in the present study. Accordingly, the observed differences should be interpreted as empirical patterns within this sample and assessment context rather than as evidence of general differences between male and female students in environmental understanding or interdisciplinary ability.

Prior participation in environmental activities was significantly associated only with Linking Ideas with Different Fields. Students who had previously participated in environmental activities obtained descriptively higher scores on this dimension than those who had not participated, whereas no significant participation-related differences were found in Design and Drawing or Description and Interpretation. The effect size for Linking Ideas with Different Fields was small ($\eta p^2 = .013$), indicating that prior participation accounted for only a limited proportion of the variation in performance. Nevertheless, the dimension-specific nature of this association is noteworthy. Environmental activities may provide students with opportunities to encounter sustainability issues in applied contexts and to draw on different forms of knowledge when considering possible solutions (Celikler et al. 2023; Tan and So 2019). At the same time, the present study recorded whether students had previously participated in environmental activities but did not measure the type, duration, frequency, or educational quality of those experiences. It is therefore not possible to determine which aspects of prior participation, if any, were associated with the observed difference. Moreover, because participation was a pre-existing student characteristic rather than an experimentally manipulated condition, the finding indicates an association and should not be interpreted as evidence that environmental activities caused higher interdisciplinary performance.

At the multivariate level, the interaction between gender and prior participation in environmental activities was statistically significant. However, none of the follow-up univariate interaction effects reached statistical significance for Design and Drawing, Description and Interpretation, or Linking Ideas with Different Fields. The multivariate interaction therefore appears to reflect the combined pattern of variation across the three dimensions rather than a statistically significant interaction within any single dimension. Although the descriptive means showed some differences in the pattern of scores across gender and participation groups, these patterns should not be interpreted as evidence that environmental activities benefited one gender more than the other. Further research using longitudinal or appropriately designed intervention studies would be needed to examine how gender and prior environmental experiences may jointly relate to students' recycling-related performance.

Regarding the third research question, entrepreneurial performance varied across the four recycling tasks. The proportion of students demonstrating Innovative Entrepreneurial Features ranged from 41.8% to 62.7%, with higher proportions observed in the first two tasks than in the third and fourth tasks. This pattern suggests that students demonstrated entrepreneurial features were not uniform across recycling problems. Rather, the extent to which students incorporated an entrepreneurial element into their proposed solutions appeared to vary according to the particular task context. Because the present study did not investigate the specific task characteristics responsible for these differences, the observed variation should not be attributed to task difficulty or content without further evidence. Nevertheless, the findings show that innovative entrepreneurial features were evident in students' responses across all four recycling contexts, although the proportions varied across tasks.

These findings complement evidence from the Omani school context. Ambusaidi et al. (2024) found that a sustainable environmental tourism education programme improved Grade 8 students' inclination to engage in entrepreneurship related to sustainable environmental tourism. Although both studies point to a meaningful connection between sustainability education and entrepreneurship among Omani school students, the constructs and methods used are different. Ambusaidi et al. (2024) examined students' inclination toward entrepreneurial engagement using a dedicated scale, whereas the present study examined entrepreneurial features demonstrated within students' responses to individual recycling tasks. The present findings should therefore be interpreted as evidence of task-based entrepreneurial performance rather than as evidence of established entrepreneurial competence, entrepreneurial intention, or readiness to initiate actual business ventures. Future research could examine why entrepreneurial performance varies across different environmental problem contexts and could combine performance-based tasks with validated measures of entrepreneurial intention or competence.

Importantly, the entrepreneurial features demonstrated across the four tasks should be considered alongside the substantially lower overall performance in Linking Ideas with Different Fields. These findings are not necessarily inconsistent because Entrepreneurship represented only one of the six criteria contributing to this broader dimension. A student could therefore demonstrate an innovative entrepreneurial feature in a particular recycling proposal while showing weaker connections to science, technology, mathematics, geography, or sustainability. The findings thus suggest that demonstrating an entrepreneurial aspect within a recycling solution does not necessarily imply strong interdisciplinary integration across the broader assessment dimension. This distinction further highlights the importance of interpreting performance on the Entrepreneurship criterion separately from students' broader interdisciplinary performance.

4.1 Implications and recommendations

The findings have several implications for science and environmental education. First, the relatively strong performance in Design and Drawing and Description and Interpretation, compared with the substantially lower performance in Linking Ideas with Different Fields, highlights the need to provide students with learning experiences that explicitly connect recycling and waste-management problems with multiple disciplinary perspectives. Classroom activities should therefore move beyond describing environmental problems to engaging students in tasks that require them to integrate scientific, technological, mathematical, geographical, sustainability, and entrepreneurial considerations when developing possible solutions.

Second, the association between prior participation in environmental activities and performance in Linking Ideas with Different Fields suggests that applied environmental experiences may have educational relevance for interdisciplinary learning, although the small effect size and the observational nature of this association warrant caution. Schools may therefore consider providing structured environmental activities, such as recycling challenges, waste-management projects, and locally relevant sustainability tasks, while explicitly connecting these experiences to curricular learning across disciplinary areas. Future intervention studies could examine whether such structured experiences contribute to improvements in students' interdisciplinary understanding.

Third, the entrepreneurial features demonstrated across the four recycling tasks, together with the observed variation across task contexts, indicate the potential value of incorporating environmental entrepreneurship into sustainability-related learning. Students could be provided with opportunities to develop recycling ideas across varied environmental problems into more elaborated proposals that consider environmental value, practical feasibility, and possible community applications. Teacher professional development may also support the design and assessment of interdisciplinary, context-based activities that connect environmental understanding with practical problem solving and entrepreneurial thinking.

4.2 Limitations and future research

This study has several limitations that should be considered when interpreting its findings. First, the participants were selected purposively from eight schools in two educational governorates in the Sultanate of Oman. Therefore, the findings should not be generalized to all Grade 10 students in Oman without caution. Future studies could include larger and more geographically diverse samples and employ probability-based sampling where feasible.

Second, students' conceptual understanding and entrepreneurial features were examined using a task-based assessment focused specifically on recycling materials and environmental waste management. Although this approach enabled students to demonstrate their understanding through applied responses, the findings reflect performance within the particular tasks and scoring criteria used in this study. Future research could combine task-based assessment with other sources of evidence, such as interviews, observations, or additional performance tasks, to provide a broader understanding of students' environmental and entrepreneurial thinking.

Third, the entrepreneurial features reported in this study were derived from a single entrepreneurship criterion embedded within the broader analytic scoring rubric rather than from a separate validated measure of

entrepreneurial intention or competence. Accordingly, the classification reflects the entrepreneurial features demonstrated in students' recycling proposals and should not be interpreted as a comprehensive measure of their entrepreneurial dispositions or capabilities. In addition, entrepreneurship was assessed separately within each recycling task, and the rubric did not specify cut-off scores for deriving an overall entrepreneurship classification across the four tasks. Future research could combine performance-based recycling tasks with validated measures of entrepreneurial intention, competence, or related constructs to examine how these different forms of evidence relate to one another.

Fourth, prior participation in environmental activities was examined as a pre-existing student characteristic rather than as an experimentally manipulated condition. Consequently, the significant association found between prior participation and Linking Ideas with Different Fields should not be interpreted as evidence of a causal effect. Experimental or longitudinal studies could further investigate how participation in structured environmental activities may influence students' interdisciplinary understanding over time.

Future research could also examine the effects of instructional approaches such as project-based and problem-based learning on students' understanding of sustainability, recycling, and the green economy. Comparative studies across different geographical and educational contexts, including urban and rural settings, may further clarify how contextual factors relate to students' ability to develop interdisciplinary and environmentally oriented solutions.

5 Conclusion

This study provides evidence that Omani Grade 10 students were more successful in representing and explaining recycling-related solutions than in connecting those solutions across disciplinary fields. The findings also showed that gender- and prior-participation differences were dimension-specific rather than consistent across the assessment, while entrepreneurial features varied across recycling-task contexts. Taken together, the results highlight the importance of assessing environmental understanding through applied tasks that require students not only to explain ideas but also to integrate scientific, technological, mathematical, geographical, sustainability, and entrepreneurial considerations. Within the limits of the purposive sample and task-based assessment, the study contributes context-specific evidence that may inform the development of more interdisciplinary and applied approaches to recycling and sustainability education in Oman.

References

Abbas Q, Imran M, Sattar A (2025) From linear to circular: The impact of economic policies and technological innovations on greenhouse gas emissions in the Netherlands. Carbon Balance Manag 20:11. https://doi.org/10.1186/s13021-025-00297-1

Al Balushi HM, Ambusaidi AK (2023) The influence of environmental education on Omani students' self-reported environmental attitudes and behaviours. Int Res Geogr Environ Educ 32(2):90–106. https://doi.org/10.1080/10382046.2022.2154976

Ambusaidi A, Al-Dayri H, Al-Sumari M (2024) The effect of sustainable environmental tourism training on the development of eighth-grade Omani students' attitudes towards the environment and their inclination to engage

in entrepreneurship in environmental tourism projects. Cogent Educ 11(1):2400745. https://doi.org/10.1080/2331186X.2024.2400745

Ambusaidi AK, Al Fulaiti MR (2022) The impact of the Environmental Excellence Program on the knowledge, attitudes, and behaviors of 4th grade students towards waste management. Interdiscip J Environ Sci Educ 18(4):e2302. https://doi.org/10.21601/ijese/12416

Brookhart SM (2013) *How to create and use rubrics for formative assessment and grading*. ASCD, Alexandria, VA

Celikler D, Aksan Z, Yilmaz A (2023) Raising awareness in sustainable environment education: Waste batteries. Pedagog Res 8(2):em0157. https://doi.org/10.29333/pr/13002

Çoruhlu TŞ, Nas SE (2018) The impact of project-based learning environments on conceptual understanding: The "Recycling" concept. Asia-Pac Forum Sci Learn Teach 19(1):Article 15

Doppelt Y (2009) Assessing creative thinking in design-based learning. Int J Technol Des Educ 19(1):55–65. https://doi.org/10.1007/s10798-006-9008-y

Jäggle G, Posekany A, Lepuschitz W, Koppensteiner G, Zakall S, Vincze M, Merdan M (2024) Educational practices for improvement of sustainability education at secondary school level. Sci Act 61(4):207–216. https://doi.org/10.1080/00368121.2024.2376758

Jönsson A, Svingby G (2007) The use of scoring rubrics: Reliability, validity and educational consequences. Educ Res Rev 2(2):130–144. https://doi.org/10.1016/j.edurev.2007.05.002

Karakuyu A, Karafil B (2026) Recycling-based STEM education for sustainability: Effects on secondary school students' STEAM attitudes, recycling behaviours and design thinking skills. Sustainability 18(4):1820. https://doi.org/10.3390/su18041820

Laius A, Saarna R, Kont M (2024) Secondary school students' understanding of circular economy and recycling at a small rural school. Interdiscip J Environ Sci Educ 20(3):e2409. https://doi.org/10.29333/ijese/14620

McHugh ML (2012) Interrater reliability: The kappa statistic. Biochem Med 22(3):276–282. https://doi.org/10.11613/BM.2012.031

Nguyen TPL (2023) Integrating circular economy into STEM education: A promising pathway toward circular citizenship development. Front Educ 8:1063755. https://doi.org/10.3389/feduc.2023.1063755

Santiani S, Reffiane F, Winarto W (2024) Science interdisciplinary learning approach: a study interdisciplinary thinking skills and literacy environment. J Educ Learn (EduLearn) 18(4):1454–1459. https://doi.org/10.11591/edulearn.v18i4.21416

Şeker F (2023) Secondary school eighth grade students' knowledge and thoughts on recycling. Int J Educ Technol Sci 3(3):859–878.

Tan E, So H-J (2019) Role of environmental interaction in interdisciplinary thinking: From knowledge resources perspectives. J Environ Educ 50(2):113–130. https://doi.org/10.1080/00958964.2018.1531280

Türksoy E, Altıntaş G (2025) Determination of cognitive structures of primary school fourth-grade students on the concept of recycling. Kastamonu Educ J 33(3):602–611. https://doi.org/10.24106/kefdergi.1750199

UNESCO (2020) *Education for sustainable development: A roadmap*. UNESCO, Paris. https://doi.org/10.54675/YFRE1448

Zhang X, Jung W, Asari M (2025) Systematic review of environmental education teaching practices in schools: Trends and gaps (2015–2024). Sustainability 17(19):8561. https://doi.org/10.3390/su17198561

Statements and Declarations

Informed Consent: Administrative permission to conduct the study in the participating schools was obtained from the Omani Ministry of Education (approval no. 2825561976). The approval encompasses all data collection procedures involving human participants as outlined in the study's methodology. All research activities were conducted in strict compliance with relevant institutional and national ethical guidelines, adhering to the principles established by the Declaration of Helsinki and its subsequent amendments.

Data availability: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests: The authors have no relevant financial or non-financial interests to disclose.

Funding: No funding was received for conducting this study.

Author contributions: Asmahan S. Alkharusi: Investigation, Methodology, Data Curation, Formal Analysis, Writing up Original Draft, and Writing up Review & Editing. Abdullah K. Ambusaidi: Supervision, Methodology, Validation, and Writing up Review & Editing. Both authors read and approved the final manuscript.