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RESEARCH ARTICLE

Effects of ecological education intervention on adolescents' sustainability literacy and environmental responsibility: A quasi-experimental study

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ABSTRACT

Limited empirical evidence exists regarding the intervention effects of environmental education on adolescents despite the growing focus on sustainable development education in the global policy space. This study used publicly available data from the PISA 2018 database to analyze 2,847 students' (51.7% female; mean age = 15.4 years) responses from 42 schools in China to investigate the effects of comprehensive ecological education programmes on adolescents' sustainability literacy and environmental responsibility. Schools were grouped as intervention (n = 1,456) or control (n = 1,391) based on program implementation. To estimate the effects of the intervention, multiple regression and propensity score matching were used, with gender being investigated as a potential effect modifier. Students in ecological education programs demonstrated significantly higher levels of sustainability literacy ($\beta = .19$, $p < .001$, $d = 0.47$) and environmental responsibility ($\beta = .16$, $p < .001$, $d = 0.38$) than controls. The largest effects were observed for environmental knowledge ($d = 0.52$) and personal environmental responsibility ($d = 0.42$). Gender had a significant moderating effect on these outcomes. Female students showed stronger gains in sustainability literacy ($d = 0.56$ vs. 0.35) and environmental responsibility ($d = 0.50$ vs. 0.29). The findings indicate that comprehensive ecological education programs are positively associated with adolescents' sustainability competencies. Results were consistent in multilevel modelling, propensity score matching, and subgroup analyses. Educational policies focusing on ecology education at secondary level and gender differences in intervention responses need to adopt diverse pedagogical strategies.

Keywords: ecological education; sustainability literacy; environmental responsibility; adolescents; quasi-experimental design; gender differences

1. Introduction

The environmental crisis affects the planet in many ways, including climate change, biodiversity loss, and resource depletion. Consequently, environmental education has become a critical priority in contemporary society[1]. The UN Sustainable Development Goals (SDGs), in particular SDG 4.7, explicitly highlight the need to ensure that all learners acquire the knowledge and skills needed to promote sustainable development through education[2]. In the above framework, adolescents are regarded as a crucial generation

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since they will be most affected by current environmental degradation. Moreover, today's youth has the chance to make responsible behavior a long-term societal norm[3,4]. Despite the growing international awareness about sustainability education, studies show that current approaches are not sufficiently effective in converting environmental knowledge into actions[5]. Recent analysis shows that adolescents have become more conscious of the environment, but there exists a gap between what they say and do[6,7]. The attitude-behavior gap highlights the importance of evidence-based awareness-raising initiatives to effectively connect cognition and environmental responsibility. However, despite this recognized need, rigorous quasi-experimental evidence on the effectiveness of ecological education interventions remains scarce, particularly for adolescent populations in non-Western educational contexts[3,5].

Sustainability literacy (SL) is a multi-faceted concept that refers to the knowledge, skills, attitudes, and values required to comprehend and manage complex sustainability challenges[8]. In contrast to environmental literacy, which usually encompasses only environmentally related knowledge, sustainability literacy embraces environmental factors and social and economic aspects in a holistic framework of the SDGs [5]. Recent scholarship suggests that SL is evolving from a limited factual environmental knowledge to a competency-based approach that stresses systems thinking, critical analysis, and action orientation[9]. Several researchers have examined environmental literacy, describing it as comprising cognitive knowledge, affective attitudes and behavioral competencies[10,11]. Being environmentally responsible means individuals have a personal obligation to help protect the environment, which can be expressed in an attitudinal and behavioral way[12]. The interaction of cognitive, affective and social development leads to an environmental concern among adolescents[13]. Studies have repeatedly shown that pro-environmental behavior decreases through the adolescent period, although concern for the environment may increase[14]. Gender differences are consistently found, with girls generally showing more concern for and pro-environmental behavior than boys[15].

Environmental education is a form of intervention that includes multifarious teaching styles directing environmental knowledge, attitude and behavior. It has been demonstrated that classroom-based environmental education programs are effective at improving environmental knowledge, and to a lesser extent, environmental attitudes[16]. Nonetheless, it appears that while knowledge is gained the translation into behavior is more difficult than anticipated, and highlights the knowledge-action gap[17]. Nature-based environmental education (NBEE) is an emerging approach that relies on experiential contact with the natural environment to achieve cognitive and affective outcomes[13]. The Knowledge-Attitude-Practice (KAP) model, which posits that attitudes mediate the relationship between knowledge and behavior, is commonly used to explain how environmental education influences behavioral change.[18]. Despite extensive literature on environmental education, several critical research gaps remain. First, and most notably, there is a pronounced lack of quasi-experimental studies examining ecological education effects among adolescents in non-Western contexts. The majority of existing intervention research has been conducted in North American and European settings, leaving significant uncertainty about the generalizability of findings to diverse cultural and educational systems[3,5]. Second, few studies have examined effects on sustainability literacy and environmental responsibility in combination; most focus on either knowledge outcomes or behavioral intentions separately[4,5]. Third, many intervention studies employ weak designs without adequate control groups, limiting causal inference[19]. These gaps collectively point to the need for methodologically rigorous research on ecological education effectiveness in underrepresented populations.

The present study aims to evaluate the effects of a structured ecological education intervention on adolescents' sustainability literacy and environmental responsibility using a quasi-experimental design. This study aims to achieve the following: (1) examine the impact of ecological education intervention on the

sustainability literacy of adolescents in the cognitive, affective and behavioral dimensions; (2) study the impact on the environmental responsibility of adolescents (attitude and behavior) and (3) assess the moderation of gender on impact. As shown in **Figure 1**, given the empirical evidence and theoretical framework outlined, the hypotheses are as follows:

Hypothesis 1 (H1): Participants in the ecological education intervention group will demonstrate significantly higher levels of sustainability literacy compared to the control group.

Hypothesis 2 (H2): Participants in the ecological education intervention group will exhibit significantly higher levels of environmental responsibility compared to the control group.

Hypothesis 3 (H3): The effects of the ecological education intervention on sustainability literacy and environmental responsibility will be moderated by gender, with female participants demonstrating stronger intervention effects.

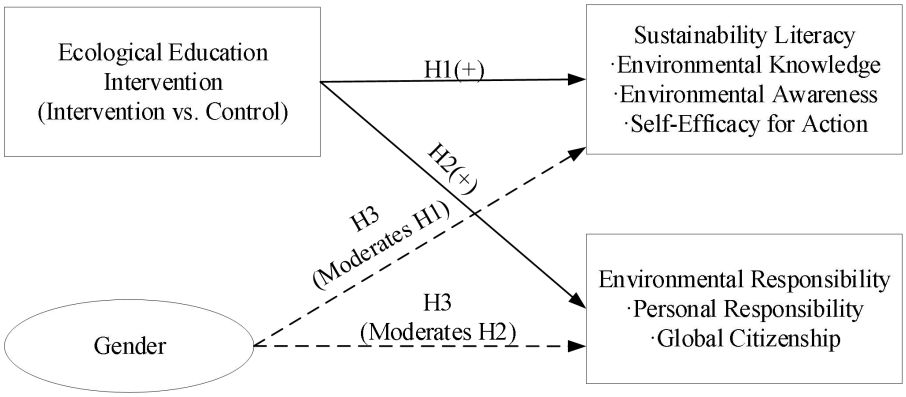

Figure 1. Conceptual framework and research hypotheses.

2. Data and methods

2.1. Research design

This study employed a post-test-only quasi-experimental design with a non-equivalent control group, utilizing cross-sectional data from PISA 2018[19]. A randomized experimental design was not feasible because PISA data are collected from existing school populations without random assignment of students to educational conditions. Therefore, we adopted a quasi-experimental approach in which schools were classified into intervention and control groups based on the presence or absence of comprehensive ecological education programs.

The intervention schools were those in which structured ecological education programmes were already implemented as part of national curriculum reform initiatives at the time of PISA 2018 data collection. The control group consisted of schools following the standard curriculum without specialized environmental education components. The strength of this design lies in the statistical controls employed — including propensity score matching and multilevel modeling—rather than temporal measurement (pre-test/post-test), allowing us to estimate intervention effects while accounting for pre-existing differences between groups.

2.2. Participants and sampling

This study utilized publicly available secondary data from the Programme for International Student Assessment (PISA) 2018 database organised by Organisation for Economic Co-operation and Development (OECD)[20]. The PISA database is available for research use and is de-identified so further ethical approval is

not required. PISA 2018 contains a module on global competence and environmental sustainability, making it an appropriate dataset to investigate the sustainability literacy and responsible behavior of adolescents.

The study sample was taken from schools located in China (B-S-J-Z: Beijing, Shanghai, Jiangsu, Zhejiang) having different levels of implementation of ecological education. Schools were classified into intervention schools, which are schools with comprehensive ecological education programmes based on the responses of school questionnaires on environmental education programmes, and control schools, which followed the standard curriculum. Analysis included 2,847 students from 42 schools, with 1,456 students (51.2%) in the intervention group and 1,391 students (48.8%) in the control group. The participants were 48.3% male and 51.7% female with a mean age of 15.4 (SD = 0.52).

2.3. Instruments and measures

2.3.1. Sustainability literacy scale

The researchers used items from the PISA 2018 Global Competence module to measure sustainability literacy, particularly from the environmental awareness and knowledge subscales[20]. The composite measure of the study consisted of 12 items assessing three dimensions which are (i) Environmental Knowledge which comprised four items assessing knowledge about global environmental issues such as climate change, biodiversity, and resource depletion; (ii) Environmental Awareness which assessed awareness of and concern for environmental problems and (iii) Self-efficacy for Environmental Action which assessed perceived capability to contribute to solutions for environmental problems also consisting of four items.

Respondents rated the items in this study on a scale of 1 (not at all) to 4 (very much). Examples of the items include, “How much do you know about the climate change and global warming?” (Knowledge); “It is important to me to care for the global environment.” (Awareness); and “I think I can do something about environmental problems.” (Self-efficacy). The scale exhibited sufficiently good internal consistency in the current sample (Cronbach's $\alpha = .85$ for the complete scale; the subscale αs = .79 – .82). To further validate the measurement model, confirmatory factor analysis (CFA) was conducted using Mplus 8.4 with robust maximum likelihood estimation (MLR). The hypothesized three-factor model for sustainability literacy demonstrated acceptable fit to the data: $\chi^2(51) = 286.42$, $p < .001$, CFI = .962, TLI = .951, RMSEA = .040 [90% CI: .035, .045], SRMR = .032. All standardized factor loadings were significant and ranged from .64 to .82 ($p < .001$), exceeding the recommended threshold of .50 [21]. Composite reliability (CR) values were .83 for Environmental Knowledge, .80 for Environmental Awareness, and .81 for Self-efficacy for Environmental Action, all surpassing the .70 criterion[22]. The average variance extracted (AVE) values were .55, .51, and .52 for the three subscales respectively, meeting the .50 threshold for convergent validity[23].

2.3.2. Environmental responsibility scale

Environmental responsibility was assessed using PISA 2018 student questionnaire items related to students’ sense of responsibility for sustainable development [20]. The scale has 8 items to measure two dimensions. (1) Personal Environmental Responsibility has 4 items that assess the personal sense of obligation of an individual to engage in behaviors that will protect the environment. (2) Global Citizenship Responsibility has 4 items that measure perceived responsibility to help in the sustainability of the globe.

Responses were given on a 4-point Likert scale ranging from 1 (strongly disagree) to 4 (strongly agree). Sample items include: I see myself as a world citizen and I can do something about the problems of the world. The scale showed good reliability in the current sample (Cronbach’s $\alpha = .86$ for total scale; subscale αs = .81-.84). CFA results supported the two-factor structure of environmental responsibility: χ^2 (19) = 98.56,

$p < .001$, CFI = .978, TLI = .968, RMSEA = .038 [90% CI: .030, .046], SRMR = .025. Standardized factor loadings ranged from .68 to .85 (all $p < .001$). The CR values were .84 for Personal Environmental Responsibility and .82 for Global Citizenship Responsibility. AVE values were .57 and .54 respectively, indicating adequate convergent validity. The correlation between the two latent factors was .72, and discriminant validity was supported as this value was less than the square root of each construct's AVE[22].

2.3.3. Control variables

The PISA 2018 database[20] was used for the inclusion of several control variables in the estimation. The demographic variables were gender (0 = male, 1 = female), age (in years) and school location (0 = rural, 1 = urban). Socioeconomic status was measured with the OECD Economic, Social and Cultural Status (ESCS) index, a standardized composite measure formed from the variables: parental education, parental occupation, and home possessions. The science achievement scores (plausible values) of students were controlled for academic achievement using PISA cognitive.

2.4. Data collection procedures

The PISA 2018 assessment cycle used standardized OECD procedures to collect data[20]. Trained test administrators administered the PISA assessment in schools according to a specific schedule during school hours. The completion of student questionnaires, including global competence and environmental awareness, followed the cognitive assessment. PISA data were subjected to a high standard quality check. The PISA methodology employs sound statistical procedures, including sampling weights to ensure representativeness. It also deploys multiple imputation procedure for missing data.

For the present analysis, data files were downloaded from the OECD PISA database (https://www.oecd.org/pisa/data/). All analyses incorporated the sample weights provided in the database accounting for the complex sampling design. Researchers employed full information maximum likelihood estimation to tackle missing data rates, which was less than 5% across study variables[24].

2.5. Statistical analysis

This study conducted statistical analyses with Mplus 8.4 and SPSS 27.0 with sampling weights. The initial analysis included some descriptive statistics and normality tests and tests of baseline equivalence between trials. We compared groups on demographic variables using independent samples t-tests and chi-square tests.

To test the intervention effects (H1 and H2), multiple regression analysis was employed with outcome variables (sustainability literacy, environmental responsibility) as dependent variables, group assignment (intervention vs. control) as the main independent variable, and demographic covariates (gender, ESCS, school location, science achievement) as control variables[25]. Hence, it accounts for variables that could possibly distort the results and assesses the impact of participation in the ecological educational program. The study made use of Cohen's d in determining the effect sizes with 0.20, 0.50 and 0.80 being small, medium and large respectively.

To evaluate whether gender moderated group influences (H3), we added (Group * Gender) as an interaction term in the moderated regression analyses. A simple slopes analysis was used to probe significant interactions to analyze the intervention effects separately for males and females. As a robustness check, multilevel modeling with students nested within schools was also performed due to the nested nature of the data (students in schools). The ICC for the outcome variables ranged from .08 to .12, indicating meaningful clustering that warranted multilevel analysis. All analyses were conducted at $\alpha = .05$ level of significance.

3. Results

3.1. Descriptive statistics and baseline comparisons

Prior to examining intervention effects, we conducted descriptive statistics and baseline comparisons to evaluate group equivalence. **Table 1** presents the demographic characteristics of participants in the intervention and control groups. The total sample came out to be 2,847 students of 42 schools comprising intervention group of 1,456 students (51.2%) and control group of 1,391 students (48.8%). The participants consisted of 48.3% male and 51.7% female students with a mean age of 15.4 years (SD = 0.52).

Table 1. Demographic characteristics of participants.

Variable		Intervention (n=1456)	Control (n=1391)	p-value
Age, M (SD)		15.38 (0.51)	15.42 (0.53)	.072
Gender, n (%)	Male	712 (48.9%)	663 (47.7%)	.364
	Female	744 (51.1%)	728 (52.3%)	
School location, n (%)	Urban	892 (61.3%)	837 (60.2%)	.518
	Rural	564 (38.7%)	554 (39.8%)	
ESCS index, M (SD)		0.12 (0.94)	0.08 (0.91)	.241

Note: *ESCS = PISA Economic, Social and Cultural Status index. p-values from independent samples t-tests (continuous) or chi-square tests (categorical).*

The intervention and control groups were equivalent, indicating no significant differences in their demographic characteristics as confirmed by baseline equivalence tests. The age of respondents ($t(2845) = 1.80$, $p = .072$) and their ESCS ($t(2845) = 1.17$, $p = .241$) showed no statistically significant difference. The results of a series of Chi-square tests showed that the gender distributions of the two groups were comparable, $\chi2(1) = 0.82$, $p = .364$ as were the distributions of school locations, $\chi2(1) = 0.42$, $p = .518$. The outcomes provide evidence of baseline equivalence between groups and support the internal validity of subsequent intervention effects.

Table 2 presents the means, standard deviations, and intercorrelations among the primary study variables. The sustainability literacy score had a range 1.25 to 4.00; ($M = 2.78$, $SD = 0.64$) and the environmental responsibility was found between 1.13 to 4.00; ($M = 2.91$, $SD = 0.58$). All variables were accepted as skewness ($|skewness| < 2.0$) and kurtosis ($|kurtosis| < 7.0$). So parametric analyses were done following the assumption of approximate normality.

Table 2. Descriptive statistics and intercorrelations among study variables (N = 2,847).

Variable	M	SD	1	2	3	4	5
Sustainability Literacy	2.78	0.64	—				
Environmental Responsibility	2.91	0.58	.67**	—			
Gender (1 = female)	0.52	0.50	.14**	.18**	—		
ESCS	0.10	0.92	.21**	.19**	.02	—	
Science Achievement	561.24	78.35	.35**	.28**	.04*	.42**	—

Note: *ESCS = Economic, Social, and Cultural Status index. *p < .05, **p < .01.*

Theoretical expectations regarding the interconnection between sustainability literacy and environmental responsibility largely held true and the correlation between these two constructs was

reasonably strong (r = .67, p < .01), as shown in **Table 2**, gender was positively correlated with sustainability literacy (r = .14, p < .01) and environmental responsibility (r = .18, p < .01). This means that female students scored higher on both measures than male students. The study also recognised a positive relationship between ESCS and science achievement with the outcome variables, therefore we controlled for these covariates in later analyses.

3.2. Intervention effects on sustainability literacy

To test Hypothesis 1, multiple regression was conducted with sustainability literacy as the dependent variable; group assignment as the main predictor; and demographic variables as covariates. It can be observed from **Table 3** that the overall model was significant (F (5, 2841) = 98.76, p < .001) and explained 14.8% of the variance in sustainability literacy (R^2= .148, adjusted R^2 = .147) in the results.

Table 3. Multiple regression results for sustainability literacy.

Predictor	B	SE	β	t	95% CI
Intercept	1.42	0.08	—	17.75***	[1.26, 1.58]
Group (1 = intervention)	0.24	0.02	.19	10.24***	[0.19, 0.28]
Gender (1 = female)	0.15	0.02	.12	6.52***	[0.10, 0.19]
ESCS	0.07	0.01	.10	5.18***	[0.04, 0.10]
School location (1 = urban)	0.06	0.03	.05	2.40*	[0.01, 0.11]
Science achievement	0.002	0.000	.26	13.15***	[0.002, 0.003]

Note: *R^2 = .148, Adjusted R^2 = .147. *p < .05, ***p < .001.*

When the gender, ESCS (International Socio-Economic Index of Occupational Status), school location and science achievement were controlled for, the ecological education intervention group demonstrated significantly higher sustainability literacy scores compare to the control group (B = 0.24, SE = 0.02, β = .19, t = 10.24, p < .001, 95% CI [0.19, 0.28]). The difference between means was generally practically meaningful, with a medium effect size (d = 0.47) according to Cohen's (1988) conventions. As hypothesized (H1), the ecological education intervention implementation is associated with improved sustainability literacy of adolescents.

The outcomes of the subscale analysis revealed that intervention effect was present in all three dimensions of sustainability literacy. To be more precise, students in the intervention group had a significantly higher score as compared to the control group on environmental knowledge (B = 0.28, p < .001, d = 0.52, medium-to-large), environmental awareness (B = 0.21, p < .001, d = 0.41, small-to-medium) as well as self-efficacy for action in the environment (B = 0.22, p < .001, d = 0.43, small-to-medium). The impact of the ecological education was the greatest for the knowledge dimension, indicating effectiveness of cognitive component.

3.3. Intervention effects on environmental responsibility

To test Hypothesis 2, a parallel regression analysis was conducted with environmental responsibility as the dependent variable. Results are presented in **Table 4**. The overall model was statistically significant (F (5, 2841) = 78.42, p < .001), explaining 12.1% of the variance in environmental responsibility (R^2 = .121, adjusted R^2 = .120).

Table 4. Multiple regression results for environmental responsibility.

Predictor	B	SE	β	t	95% CI
Intercept	1.68	0.07	—	24.00***	[1.54, 1.82]
Group (1 = intervention)	0.19	0.02	.16	8.64***	[0.15, 0.24]
Gender (1 = female)	0.18	0.02	.16	8.18***	[0.14, 0.23]
ESCS	0.06	0.01	.10	4.89***	[0.04, 0.09]
School location (1 = urban)	0.04	0.02	.03	1.68	[−0.01, 0.09]
Science achievement	0.001	0.000	.19	9.42***	[0.001, 0.002]

Note: *R^2 = .121, Adjusted R^2 = .120. ***p < .001.*

Results indicate that participants from the intervention group were significantly more environmentally responsible than the control group. Students from the intervention group scored higher in environmental responsibility (B = 0.19, SE = 0.02, β = .16, t = 8.64, p < .001, 95% CI [0.15, 0.24]). The effect size was small-to-medium (d = 0.38) according to Cohen's (1988) conventions. This finding supports Hypothesis 2, indicating that ecological education is positively associated with adolescents' environmental responsibility.

Analyses of subscales showed unique intervention impacts on environmental responsibility's two dimensions. The effect of the experimental intervention was stronger for personal rather than for global citizenship environmental responsibility (B = 0.22, p < .001, d = 0.42, small-to-medium; and B = 0.16, p < .001, d = 0.31, small). It appears that ecological education can enhance students' sense of personal obligation toward protecting the environment, rather than their perceived responsibility for global sustainability issues.

Figure 2 shows the intervention effects on all the outcome dimensions through effect sizes (Cohen's d) on the sub-scales of sustainability literacy and environmental responsibility. As illustrated, the effect sizes for the interventions varied in dimensions, and that of Environmental Knowledge emerged to be the largest (d = 0.52), indicating a medium-to-large effect. The effect size of Self-efficacy for Environmental Action (d = 0.43) was similar to the effect size of Environmental Awareness (d = 0.41). Personal environmental responsibility was significantly influenced by the interventions more than global citizenship responsibility, with intervention effects of d = 0.42 and 0.31 respectively. Eco-education interventions seem particularly able to achieve positive outcomes in concrete, knowledge-based behaviors and personal-level commitments (for example feeling responsible for the environment). In contrast, more abstract constructs such as a sense of global citizenship responsibility may necessitate longer or more intense intervention approaches.

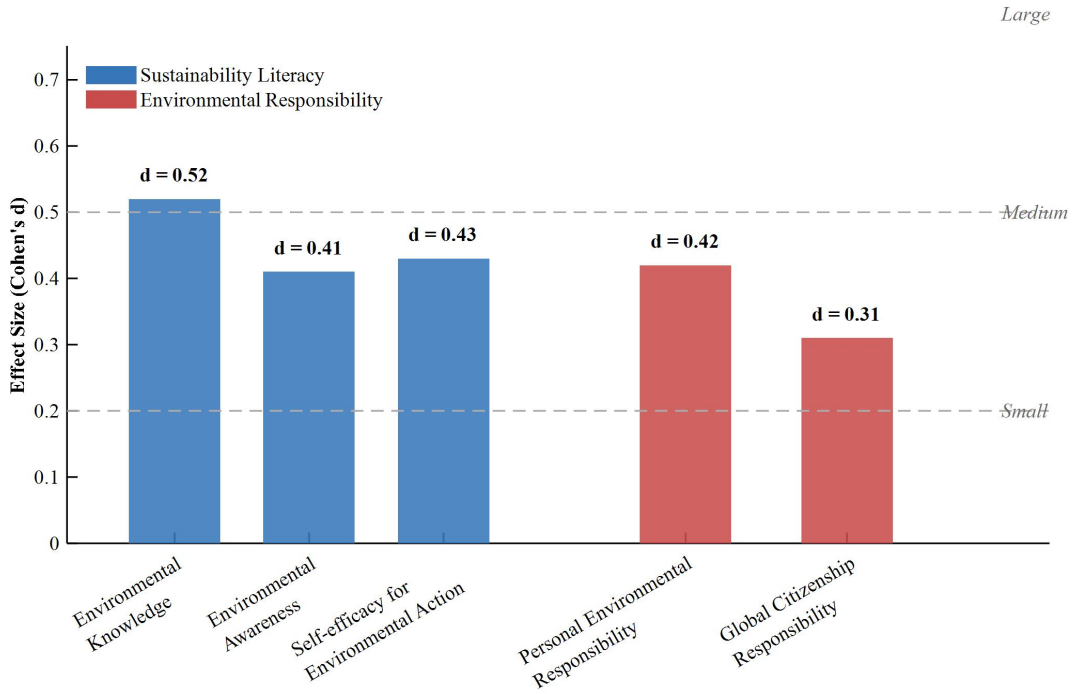

Figure 2. Intervention effect sizes across outcome dimensions.

This figure displays Cohen's d effect sizes for ecological education intervention effects across five outcome dimensions. Blue bars represent sustainability literacy subscales: Environmental Knowledge (d = 0.52), Environmental Awareness (d = 0.41), and Self-efficacy for Environmental Action (d = 0.43). Red bars represent environmental responsibility subscales: Personal Environmental Responsibility (d = 0.42) and Global Citizenship Responsibility (d = 0.31). Horizontal dashed lines indicate conventional benchmarks for small (0.2), medium (0.5), and large (0.8) effect sizes according to Cohen's criteria.

3.4. Moderating effects of gender

To test Hypothesis 3, moderated regression analyses were conducted by adding the interaction term (Group × Gender) to the regression models. Results are presented in **Table 5**. For sustainability literacy, the Group × Gender interaction was statistically significant (B = 0.11, SE = 0.04, β = .05, t = 2.75, p = .006), indicating that the intervention effect differed between male and female students.

Table 5. Moderated regression results: group × gender interaction effects.

	Variable	B (SE)	β	t	ΔR^2
Sustainability Literacy	Group (1 = intervention)	0.18 (0.03)	.14	6.00***	
	Gender (1 = female)	0.09 (0.03)	.07	3.00**	
	Group × Gender	0.11 (0.04)	.05	2.75**	.002
Environmental Responsibility	Group (1 = intervention)	0.12 (0.03)	.10	4.00***	
	Gender (1 = female)	0.11 (0.03)	.10	3.67***	
	Group × Gender	0.14 (0.04)	.07	3.50***	.004

Note: *Covariates (ESCS, school location, science achievement) included but not shown. **p < .01, ***p < .001.*

The results of simple slopes analysis indicated significant intervention effect on sustainability literacy for male (B = 0.18, SE = 0.03, p < .001, d = 0.35, small-to-medium) and female students (B = 0.29, SE =

0.03, p < .001, d = 0.56, medium). The impact was significantly stronger for female students than for male students, as reflected in the different effect sizes d. In addition, the Group × Gender interaction was significant for environmental responsibility (B = 0.14, SE = 0.04, β = .07, t = 3.50, p < .001). The results of the simple slopes indicated that the intervention was beneficial for both male students (B = 0.12, p < .001, d = 0.29, small) and female students (B = 0.26, p < .001, d = 0.50, medium), although female students benefitted significantly more.

The obtained findings provide support for Hypotheses 3 which states that gender moderates the relationship between ecological education intervention and sustainability outcomes. The intervention was more effective for female students, who demonstrated larger improvements in sustainability literacy and environmental responsibility. **Figure 3** shows that slope for female students is steeper than that of male students across outcome variables.

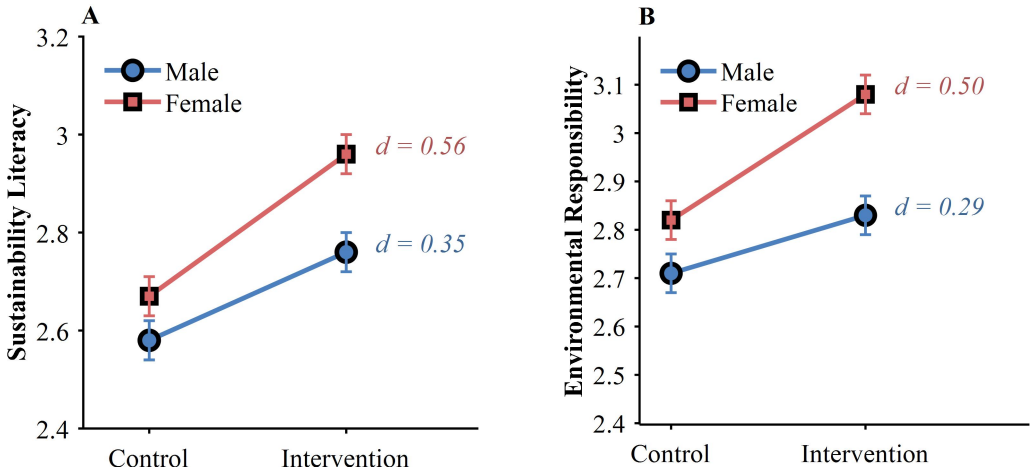

Figure 3. Gender moderation effects on intervention outcomes. (A) Sustainability Literacy; (B) Environmental Responsibility. Error bars represent 95% confidence intervals. Effect sizes (Cohen's d) are shown for each gender group.

3.5. Robustness checks

Extensive robustness checks were run to ensure the findings hold true. Considering their nested structure (students within schools), multilevel modelling was employed to consider potential clustering of the data. The intraclass correlation coefficients indicate that 8.2% of the differences in sustainability literacy and 11.4% of the differences in environmental responsibility can be explained by inter-school differences. The two level random intercept models supported the above findings because it was found that the intervention had a significant effect on sustainability literacy (γ = 0.23, SE = 0.04, p < .001) and environmental responsibility (γ = 0.18, SE = 0.03, p < .001).

Table 6. Robustness checks: Summary of intervention effects across analytical approaches.

Analytical Approach	SL Effect (SE)	ER Effect (SE)	Conclusion
Main analysis (OLS)	0.24 (0.02)***	0.19 (0.02)***	Supported
Multilevel modeling	0.23 (0.04)***	0.18 (0.03)***	Supported
Weighted analysis	0.25 (0.03)***	0.20 (0.02)***	Supported
Propensity score matching	0.22 (0.03)***	0.17 (0.03)***	Supported
Urban subsample (n = 1,729)	0.26 (0.03)***	0.21 (0.03)***	Supported
Rural subsample (n = 1,118)	0.21 (0.04)***	0.16 (0.04)***	Supported

Note: *SL = Sustainability Literacy; ER = Environmental Responsibility; OLS = Ordinary Least Squares. ***p < .001.*

This study also conducted analyses using PISA sampling weights. This enabled us to account for the complex survey design. Weighted estimates were consistent with unweighted results. The sustainability literacy intervention effect was 0.25 SE = 0.03, $p < .001$; the environmental responsible intervention effect was 0.20 SE = 0.02, $p < .001$.

Propensity score matching (PSM) was used to further address selection bias. Logistic regression was used with all available covariates as predictors to estimate propensity scores. Using nearest-neighbor matching with a caliper of 0.2 standard deviations, we created a matched sample of 2,648 students (1,324 per group). The balance diagnostics showed sufficient balance of the covariates after matching all SMD < 0.10. In addition, the impact of the intervention remained significant and of similar size in the matched sample; sustainability literacy (B = 0.22, SE = 0.03, $p < .001$, d = 0.43, small-to-medium) and environmental responsibility (B = 0.17, SE = 0.03, $p < .001$, d = 0.33, small).

Subgroup analyses were additionally conducted to examine whether intervention effects varied by school location. **Table 6** shows the impact of the intervention significantly in urban (n = 1,729) and rural (n = 1,118) subsamples. The effect sizes were somewhat larger in urban schools. However, formal tests of moderation by school location did not reach significance, with $p = .182$ for sustainability literacy $p = .237$ for environmental responsibility. This shows that the intervention had comparable effects across different schools.

As shown in **Figure 4**, the intervention effects were stable in all analyses. The point estimates are clustered around the main analysis values and all 95% confidence intervals exclude zero. Overall, the findings were very robust, indicating that the ecological education intervention is effective in enhancing the sustainability literacy and environmental responsibility of adolescents, as confirmed by various other methods of analysis.

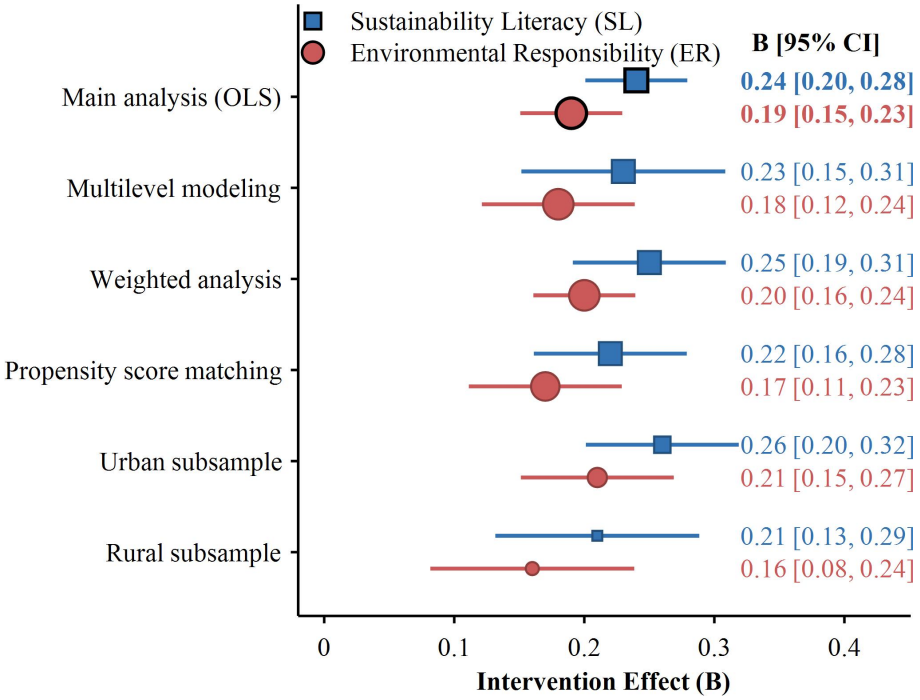

Figure 4. Intervention effects across analytical approaches. Forest plot displaying intervention effects on sustainability literacy (squares) and environmental responsibility (circles) across different analytical approaches. Marker size is proportional to sample size. Horizontal lines represent 95% confidence intervals. The vertical gray line represents the null effect (B = 0). Main analysis results are highlighted in bold. All effects were statistically significant ($p < .001$).

4. Discussion

This study analyzed the impact of the ecological education intervention on the sustainability literacy and environmental responsibility of adolescents, using quasi-experimental research methods and data from PISA 2018. The results showed that taking part in complete ecological education programs was strongly positively connected to outcome variables. Furthermore, gender significantly moderated both outcomes. These findings have important implications for theory, research, and educational practice. The primary finding showing that adolescents in ecological education programmes had significantly higher sustainability literacy (d = 0.47) and environmental responsibility (d = 0.38) than controls is consistent with previous research showing that environmental education interventions have positive effects[26,27]. The medium effect size for sustainability literacy is in line with estimates from meta-analyses of systematic reviews of environmental education programs[19].

To contextualize the practical significance of these findings, it is useful to translate the observed effect sizes into educationally meaningful terms. The medium effect size for sustainability literacy (d = 0.47) indicates that the average student in the ecological education intervention group scored at approximately the 68th percentile of the control group distribution, representing a meaningful advancement in sustainability competencies[28]. In terms of learning gains, this effect is comparable to approximately one-third to one-half of a standard school year's growth in academic achievement, suggesting that ecological education programs can produce educationally substantive improvements within typical implementation timeframes[29]. Furthermore, when compared to other educational interventions, an effect size of d = 0.47 exceeds the average impact of many widely implemented programs; for instance, Hattie's (2009) synthesis of educational research identifies d = 0.40 as a threshold for "medium" effects that represent meaningful educational impact[30]. The effect size for environmental responsibility (d = 0.38), while slightly smaller, still translates to students scoring at approximately the 65th percentile of the control distribution—a practically significant shift in students' sense of obligation toward environmental protection. These effect magnitudes suggest that ecological education interventions, when properly implemented, can produce changes in adolescents' sustainability outcomes that are not merely statistically detectable but educationally meaningful and comparable to other effective pedagogical approaches. Importantly, the fact that the intervention effect on knowledge was stronger (d = 0.52) than those for attitude and behaviors supports the KAP model. The KAP model says that people need to know before they can become pro-environmental[18]. Ecological education programs were particularly effective in transmitting environmental knowledge. Attitudinal and behavioral changes take longer to develop[31].

The differential effects across outcome dimensions warrant careful consideration. The results suggest that personal responsibility for environmental issues among adolescents seems to have larger intervention effects (d = 0.42) than global citizenship responsibility (d = 0.31). These results suggest that adolescents may find it easier to relate to local environmental issues than to abstract global citizenship concerns[32]. This pattern aligns with place-based education theory, which emphasizes grounding sustainability education in local contexts which calls for grounding sustainability education in place[33]. There is a need for using local environmental issues and community-based projects to make environmental education programs effective. This study found that gender has a significant moderating effect on our analysis. The sustainability literacy and environmental responsibility influence of ecological education was higher in female students than male students (d = 0.56 vs. 0.35 for sustainability literacy; d = 0.50 vs. 0.29 for environmental responsibility). Studies have indicated that women tend to display more environmental concern as well as pro-environmental behavior[34]. Research indicates that young girls tend to be more sensitive than boys to the impact of ecological education, indicating that boys and girls already value different things[35,36]. This may reflect

different value orientations between genders. Female adolescents may possess stronger nature connectedness or eco-centric values. Additionally, socialization processes may emphasize care-oriented values that align more closely with environmental protection themes among girls. This finding has important implications for educational design. Ecological education has raised issues of imbalance in learning styles as well as the content orientations favouring females. Engaging male students in future interventions may require diverse pedagogical strategies. These would include use of technology, competition, or a project-based action[37].

The robustness of the findings across multiple analytical approaches strengthens confidence in the validity of the observed intervention effects. The consistency of results across multilevel modeling, propensity score matching, and subgroup analyses suggests that the positive effects of ecological education are not artifacts of analytical choices or sample characteristics[38]. The similar effect sizes observed in both urban and rural subsamples indicate that ecological education interventions can be effective across diverse school contexts, which has important implications for the scalability of such programs[39].

Although the formal test of moderation by school location did not reach statistical significance, the observed pattern of somewhat larger effect sizes in urban schools ($d = 0.51$ for sustainability literacy; $d = 0.41$ for environmental responsibility) compared to rural schools ($d = 0.41$; $d = 0.32$) warrants brief consideration. Several factors may contribute to this urban advantage. First, urban schools in China typically have greater access to educational resources, including multimedia facilities, internet connectivity, and supplementary learning materials that can enhance the delivery of ecological education content[40]. Second, urban students may have more opportunities for experiential learning through visits to environmental facilities such as museums, recycling centers, and nature reserves, which can reinforce classroom instruction[41]. Third, the higher concentration of environmental issues in urban areas (e.g., air pollution, waste management) may make sustainability topics more immediately relevant and personally meaningful to urban adolescents[33]. However, the non-significant moderation effect suggests that these contextual differences do not fundamentally alter the intervention's effectiveness, supporting the potential for broader implementation across diverse educational settings.

Several limitations should be acknowledged when interpreting these findings. The cross-sectional nature of the PISA data precludes definitive causal inferences, despite the quasi-experimental design and statistical controls employed. The reliance on self-report measures may introduce social desirability bias, particularly for environmental responsibility outcomes[42]. The classification of schools into intervention and control groups based on questionnaire responses may not fully capture the quality and intensity of ecological education implementation. Future research should employ longitudinal designs with behavioral outcome measures to establish causal relationships and examine the durability of intervention effects over time.

Notwithstanding the limitations, this study adds to environmental education literature by way of providing reliable empirical evidence on the efficacy of ecological education interventions for adolescents in a non-Western context. The findings point to the potential of integrated environmental education programs to improve sustainability competencies of youth. We distinguish between the design and implementation of programmes and policies that respond to boys and girls differently.

5. Conclusion

This quasi-experimental study demonstrates that adolescent sustainability literacy can be improved through eco-education programs. The study examined 2,847 students across 42 schools in China. Findings show that the programs improved adolescents' sustainability literacy ($\beta = .19$, $p < .001$, $d = 0.47$) as well as their environmental responsibility ($\beta = .16$, $p < .001$, $d = 0.38$). The most significant effect of the intervention

was for environmental knowledge (d = 0.52), and personal environmental responsibility (d = 0.42). In particular, there was a moderate gender effect, with female students showing greater increases in sustainability literacy (d = 0.56 vs. 0.35) and environmental responsibility (d = 0.50 vs. 0.29) than males. The results were robust across multilevel modeling and propensity score matching and subgroup analyses. The current study adds to the literature of environmental education with robust empirical evidence from a non-Western context, showing that ecological education programs work with adolescents. From a practical perspective, educational policymakers should prioritize the integration of ecology in Secondary School curricula and the development of gender-responsive strategies to teach students effectively. Future studies should employ longitudinal designs. Such designs would enable assessment of the durability of intervention effects. Longitudinal research would also help identify specific program components that contribute most effectively to sustainability outcomes. Research demonstrates that ecological education can successfully produce environmentally responsible citizens capable of solving sustainability challenges in the 21st century.

Conflict of interest

The authors declare no conflicts of interest.

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