Research Journal in Advanced Humanities

RJAH

https://doi.org/10.58256/19b9wq07

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RESEARCH ARTICLE **Section:** *Philosophy & Religion*

Green chemistry awareness and environmental responsibility: Exploring the cultural and ethical foundations of responsible environmental behavior among university students

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ABSTRACT

Escalating environmental degradation resulting from conventional chemical practices has intensified calls for sustainability-oriented education that shapes not only technical competence but also responsible human conduct toward the environment. While Green Chemistry has been widely studied as a scientific framework, limited scholarly attention has examined how students' awareness of its principles relates to their everyday environmental behavior, leaving a notable gap between chemical education and the social-behavioral dimensions of sustainability. This study aims to examine the relationship between awareness of Green Chemistry principles and responsible environmental behavior among university students. A quantitative correlational design was employed, involving a main sample of 687 undergraduate students from two faculties at Al-Azhar University, who completed two researcher-developed electronic scales measuring awareness of Green Chemistry principles and responsible environmental behavior. Results revealed statistically significant positive correlations between all study variables, and regression analysis confirmed that awareness dimensions—particularly waste prevention—significantly predicted responsible behavior, explaining a meaningful share of its variance. These findings underscore the value of integrating scientific awareness into broader educational and cultural strategies for cultivating environmentally responsible citizenship, offering implications for curriculum design, sustainability pedagogy, and the humanistic dimensions of science education.

KEYWORDS: green chemistry awareness, responsible environmental behavior, sustainability education, pro-environmental behavior, university students, environmental citizenship

Research Journal in Advanced Humanities
Volume 7, Issue 3, 2026
ISSN: 2708-5945 (Print)
ISSN: 2708-5953 (Online)

ARTICLE HISTORY
Submitted: **22 June 2026**
Accepted: 26 **August 2026**
Published: 07 **September 2026**

HOW TO CITE
Wizrah, M. S. I., Abdellatif, M. S., Aldosari, R. N. A., & Nemtallah, M. A. (2026). Green chemistry awareness and environmental responsibility: Exploring the cultural and ethical foundations of responsible environmental behavior among university students. *Research Journal in Advanced Humanities*, 7(3). https://doi.org/10.58256/19b9wq07

Published in Nairobi, Kenya by Royallite Global, an imprint of Royallite Publishers Limited

Introduction

Traditional chemistry has become a pressing environmental concern in the modern era because conventional industrial practices continue to generate pollution that overwhelms natural systems and threatens both human and ecological health. Chemical manufacturing has expanded rapidly worldwide, releasing large volumes of hazardous waste, toxic solvents, and persistent pollutants into air, water, and soil (Kosnik et al., 2022; Landrigan et al., 2020; Schäffer et al., 2023). These substances often resist degradation, bioaccumulate across food chains, and contribute significantly to chronic disease and biodiversity loss (Ali et al., 2019; Brack et al., 2022; Sigmund et al., 2023). Such widespread contamination underscores the inefficiency and unsustainability of conventional chemical processes, reinforcing the urgent need to promote green chemistry awareness as a pathway toward more responsible environmental behavior.

In response to the escalating environmental damage caused by conventional chemical practices, green chemistry emerged as a proactive framework for designing safer chemicals and processes. The U.S. Environmental Protection Agency formally defined it as the design of chemical products and processes that reduce or eliminate hazardous substances, a concept later codified into the Twelve Principles by Paul Anastas and John Warner in 1998 (Anastas & Beach, 2009; De Marco et al., 2018; O'Brien et al., 2009). Unlike traditional pollution control, which manages waste after it is generated, green chemistry addresses hazard at the molecular design stage, treating toxicity as a design flaw rather than an unavoidable outcome (Anastas & Beach, 2007; Cui et al., 2011; Singh, 2025). This shift toward prevention laid the conceptual foundation for promoting environmental awareness and responsible chemical practice.

The Twelve Principles of Green Chemistry, formalized by Anastas and Warner, function as an integrated design framework rather than a checklist of isolated goals and can be grouped into three broad clusters (Abdussalam-Mohammed et al., 2020; Anastas & Beach, 2007; De Marco et al., 2018). The first cluster, prevention, prioritizes eliminating waste at its source, maximizing atom economy, and minimizing unnecessary derivatization (Kharissova et al., 2019; Martinengo et al., 2024). The second, resource and energy efficiency, promotes safer solvents, catalysis, and renewable feedstocks over hazardous, resource-intensive alternatives (Mitarlis et al., 2023; Sheldon et al., 2021). The third, safety and degradability, emphasizes designing chemicals with reduced toxicity and ensuring products break down safely at the end of their life cycle (Vaccaro, 2016; Zuin et al., 2021). Together, these clusters provide a coherent foundation for evaluating environmental awareness.

Beyond the laboratory, awareness of Green Chemistry principles functions as a cognitive prerequisite that links theoretical chemical knowledge to broader sustainability reasoning and responsible decision-making in everyday life (Chen et al., 2020; Sunday et al., 2025). This awareness fosters critical and systems thinking, enabling individuals to evaluate the long-term environmental effects of their choices and to recognize the interconnections between molecular-level processes and societal outcomes (Hurst et al., 2019; Jusniar et al., 2025; Nikolovski & Stojanovska, 2025). Such cognitive development equips students and citizens to make informed consumer decisions and participate meaningfully in environmental discourse (Chang et al., 2025; Ribau, 2025). Ultimately, this awareness serves as the bridge between knowing how chemistry affects the environment and translating that knowledge into sustainable lifestyle practices and responsible civic behavior.

Responsible environmental behavior refers to deliberate, intentional actions individuals take to minimize their negative impact on the environment or actively improve it, a concept used interchangeably with pro-environmental and ecologically sustainable behavior in the literature (Fenitra et al., 2022; Musova et al., 2021; Zeng et al., 2023). This behavior manifests across three principal forms: conscious consumption, which involves purchasing decisions that account for ecological consequences; Waste Prevention Concept, encompassing recycling, energy conservation, and waste reduction; and positive environmental participation, reflected in civic engagement and advocacy for environmental protection (Han, 2021; Srisathan et al., 2024; Widayat et al., 2021). Intentionality and moral obligation serve as core distinguishing features throughout these forms, differentiating conscious environmental action from habitual or incidental conduct (Kim et al., 2021; Zeng et al., 2023).

University students constitute a key population for studying Green Chemistry awareness and environmental behavior because they simultaneously occupy the roles of future scientists, consumers, decision-makers, and agents of change for the Sustainable Development Goals (Filho et al., 2024; Kleespies & Dierkes, 2022; Zeng et al., 2023). Higher education institutions equip these students with the knowledge and skills needed to develop practical environmental solutions and to eventually assume socially influential positions in governance, industry, and policymaking (Leiva-Brondo et al., 2022; Takshe et al., 2023). As emerging consumers, students also drive demand for sustainable products and environmentally conscious brands, shaping long-term market and behavioral trends (Cayolla et al., 2023). This convergence of scientific training, consumer influence, and future authority positions students to translate sustainability education into lasting societal and environmental change (Mohammadi et al., 2023).

Theoretically, the link between environmental awareness and behavior is best explained through models such as the Knowledge-Attitude-Behavior (KAB) framework and the Theory of Planned Behavior (TPB), both of which position awareness as a cognitive antecedent that shapes action through intermediate psychological pathways (Kollmuss & Agyeman, 2002; Valencia-Arías et al., 2026). The KAB model proposes that environmental knowledge shapes attitudes, which subsequently drive behavior, although the attitude-behavior link is often characterized as weak (Jindal et al., 2025; Wang & Zhang, 2021). The TPB extends this logic by identifying behavioral intention—shaped by attitudes, subjective norms, and perceived behavioral control—as the most direct predictor of action, with awareness exerting mainly indirect effects (Araújo et al., 2025; Zhang et al., 2024). These frameworks underscore that awareness alone rarely produces behavior without mediating psychological and contextual factors.

Despite growing interest in both domains, the existing literature rarely bridges green chemistry awareness and responsible environmental behavior among university students. Most green chemistry studies focus on teaching methods, curriculum design, or knowledge acquisition rather than measuring behavioral outcomes (Alrawili et al., 2024; Ghazali & Yahaya, 2022; Sunday et al., 2025). Meanwhile, the broader pro-environmental behavior literature relies on general environmental awareness or psychological constructs without invoking green chemistry-specific knowledge (Diaz et al., 2023; Husban, 2025; Rohizan et al., 2026). Santosa et al. (2023) explicitly note the absence of research examining green chemistry knowledge in relation to environmental care behavior. This disciplinary silo leaves open whether green chemistry-specific awareness produces stronger, more consistent environmental behavior than general environmental awareness alone, underscoring the need for the present study.

Building on this theoretical and empirical background, the present study aims to examine the relationship between awareness of Green Chemistry principles and responsible environmental behavior among university students. The study seeks to describe the levels of awareness of Green Chemistry principles and its three dimensions, namely Waste Prevention Concept, Resource and Energy Efficiency, and Safety and Degradability, alongside the levels of responsible environmental behavior and its dimensions of Conscious Consumption, Pollution Prevention, and Positive Participation. It further investigates the bivariate relationships linking these dimensions and examines the extent to which awareness of Green Chemistry principles predicts responsible environmental behavior, thereby clarifying whether domain-specific scientific awareness translates meaningfully into students' everyday environmentally responsible conduct.

Method

Participants

The present study relied on a two-stage sampling design comprising a psychometric (pilot) sample used to establish the reliability and construct validity of the study instruments, and a main sample used to test the relationship between awareness of Green Chemistry principles and responsible environmental behavior. The psychometric sample consisted of 593 undergraduate students, while the main study sample consisted of 687 undergraduate students. Participants were recruited from the Faculty of Education (Boys), Dakahlia, and the Faculty of Humanities, Dakahlia, both affiliated with Al-Azhar University, using a convenience sampling technique. Eligibility criteria required that participants be currently enrolled undergraduate students who voluntarily agreed to take part after being informed of the purpose of the study and their right to withdraw at any stage. The demographic characteristics of the psychometric and the main samples, including residence, gender, academic year, and age, are presented in Table 1.

Table 1. Demographic Characteristics of the Psychometric Sample and the Main Study Sample

Demographic Variable		Psychometric Sample (N = 593)		Main Sample (N = 687)	
Variable	**Category**	**f**	**%**	**f**	**%**
Residence	Rural	240	40.5	299	43.5
	Urban	353	59.5	388	56.5
Gender	Male	203	34.2	233	33.9
	Female	390	65.8	454	66.1
Academic Year	First	177	29.8	204	29.7
	Second	152	25.6	185	26.9
	Third	149	25.1	182	26.5
	Fourth	115	19.4	116	16.9
Age (years)	M (SD)	19.42 (1.03)		19.44 (1.00)	
	Range: 18–22	—		—	

As shown in Table 1, the two samples were broadly comparable in terms of demographic composition, with a predominance of female and urban-residing participants in both samples, which supports the appropriateness of generalizing the psychometric findings to the main study sample.

Instruments

Awareness of Green Chemistry Principles (AGCP) Scale was measured using a scale developed by the researchers based on Anastas and Warner's Twelve Principles of Green Chemistry. The scale consists of 13 items distributed across three dimensions: Waste Prevention Concept (4 items), Resource and Energy Efficiency (5 items), and Safety and Degradability (4 items). Responses were recorded on a five-point Likert-type scale ranging from 1 (strongly disagree) to 5 (strongly agree), yielding total scores ranging from 13 to 65, with higher scores indicating greater awareness of Green Chemistry principles. Internal consistency reliability, assessed through Cronbach's alpha (α), was acceptable to good across the three dimensions (WPC: $\alpha = .79$; REE: $\alpha = .758$; SD: $\alpha = .75$), and good for the total scale ($\alpha = .828$). Construct validity was further examined through confirmatory factor analysis (CFA) of the three-factor structure, which yielded an acceptable fit to the data: chi-square to degrees of freedom ratio (χ^2/df) = 2.18, Comparative Fit Index (CFI) = .961, Tucker–Lewis Index (TLI) = .952, Root Mean Square Error of Approximation (RMSEA) = .042, and Standardized Root Mean Square Residual (SRMR) = .036, indicating that the hypothesized three-factor structure adequately represented the underlying data.

Responsible Environmental Behavior (REB) Scale was measured using a scale developed by the researchers, comprising 14 items distributed across three dimensions: Conscious Consumption (5 items), Pollution Prevention (4 items), and Positive Participation (5 items). Items were rated on the same five-point Likert-type format described above, with total scores ranging from 14 to 70 and higher scores reflecting a greater tendency toward responsible environmental behavior. Internal consistency reliability was good across dimensions (CC: $\alpha = .811$; PP: $\alpha = .775$; PPart: $\alpha = .812$) and for the total scale ($\alpha = .846$). Confirmatory factor analysis confirmed the three-factor structure of the scale, yielding an acceptable model fit: χ^2/df = 2.31, CFI = .957, TLI = .948, RMSEA = .045, and SRMR = .039.

Procedure

Data were collected electronically through a Google Forms questionnaire administered to undergraduate students at the Faculty of Education (Boys), Dagahlia, and the Faculty of Humanities, Dagahlia, Al-Azhar University, during the second semester of the 2025/2026 academic year. Prior to data collection, ethical approval was obtained, and informed consent was secured from all participants electronically. Participants were informed of the purpose of the study, assured of the confidentiality and anonymity of their responses, and advised that participation was entirely voluntary. The electronic form began with the demographic questionnaire, followed by the AGCP scale and then the REB scale.

Data Analysis

Data were analyzed using the Statistical Package for the Social Sciences (SPSS). Descriptive statistics, including means, standard deviations, frequencies, and percentages, were computed to summarize participant characteristics and study variables. Confirmatory factor analysis was conducted to verify the factorial structure of both scales, and Cronbach's alpha was used to assess internal consistency reliability. Pearson correlation coefficients and multiple regression analysis were subsequently employed to examine the relationship between awareness of Green Chemistry principles and its dimensions and responsible environmental behavior among university students.

Results

Findings are presented in three stages: descriptive statistics for awareness of Green Chemistry principles and responsible environmental behavior and their dimensions, Pearson correlation analysis to examine relationships among the study variables, and multiple linear regression analysis to assess the predictive power of Green Chemistry awareness dimensions for responsible environmental behavior. Table 2 presents the descriptive statistics, including the minimum, maximum, mean, and standard deviation, for the three dimensions of awareness of Green Chemistry principles and their total score, as well as for the three dimensions of responsible environmental behavior and their total score, based on the main study sample.

Table 2. Descriptive Statistics for Awareness of Green Chemistry Principles and Responsible Environmental Behavior

Variable	Min	Max	M	SD
Waste Prevention Concept	4.00	20.00	14.35	3.44
Resource & Energy Efficiency	5.00	25.00	17.69	4.22
Safety & Degradability	4.00	20.00	14.23	3.47
Total AGCP	20.00	65.00	46.27	8.27
Conscious Consumption	5.00	25.00	18.03	4.46
Pollution Prevention	4.00	20.00	14.17	3.73
Positive Participation	5.00	25.00	17.90	4.44
Total REB	21.00	70.00	50.09	9.64

As shown in Table 2, participants reported moderately high levels of both awareness of Green Chemistry principles and responsible environmental behavior relative to the possible range of each scale. Among the dimensions of awareness, Resource and Energy Efficiency yielded the highest mean score, whereas Safety and Degradability yielded the lowest. With respect to responsible environmental behavior, Conscious Consumption and Positive Participation showed comparable mean levels, both exceeding the mean level reported for Pollution Prevention. The standard deviations indicate a reasonable degree of variability in participants' responses across all dimensions, supporting the suitability of the data for subsequent correlational and predictive analyses.

Prior to testing the predictive relationships among study variables, Pearson product-moment correlation coefficients were computed to examine the bivariate associations among the dimensions and total scores of awareness of Green Chemistry principles and responsible environmental behavior. The results of this analysis are presented in Table 3.

Table 3. Pearson Correlation Matrix Among Study Variables

Variable	1	2	3	4	5	6	7	8
1. Waste Prevention Concept	1							
2. Resource & Energy Efficiency	.309**	1						
3. Safety & Degradability	.336**	.328**	1					
4. Total AGCP	.715**	.777**	.727**	1				
5. Conscious Consumption	.272**	.258**	.193**	.326**	1			
6. Pollution Prevention	.284**	.260**	.225**	.346**	.369**	1		

Variable	1	2	3	4	5	6	7	8
7. Positive Participation	.281**	.240**	.282**	.358**	.347**	.406**	1	
8. Total REB	.365**	.330**	.306**	.449**	.765**	.745**	.778**	1

As shown in Table 3, all correlation coefficients among the study variables were positive and statistically significant at the 0.01 level. The total score of awareness of Green Chemistry principles was significantly and positively correlated with the total score of responsible environmental behavior, indicating that students who reported greater awareness of Green Chemistry principles also tended to report a stronger inclination toward responsible environmental behavior. Among the three dimensions of awareness, Resource and Energy Efficiency exhibited the strongest association with the total awareness score, while all three dimensions showed moderate positive correlations with the total score of responsible environmental behavior. Within the responsible environmental behavior scale, the three dimensions were strongly and positively correlated with their own total score, with Positive Participation showing the strongest contribution. These findings support the theoretical assumption that awareness of Green Chemistry principles is meaningfully linked to responsible environmental behavior and justify proceeding to regression analysis to determine the predictive contribution of each dimension of awareness.

To examine whether the dimensions of awareness of Green Chemistry principles significantly predict responsible environmental behavior, a standard multiple linear regression analysis was conducted, with Waste Prevention Concept, Resource and Energy Efficiency, and Safety and Degradability entered simultaneously as predictors and the total score of responsible environmental behavior entered as the criterion variable. The overall model fit and analysis of variance results are presented in Table 4.

Table 4. Model Summary and Analysis of Variance for the Regression of Responsible Environmental Behavior on Awareness of Green Chemistry Dimensions

Source	R / df	R^2 / MS	F	Sig.
Model Summary	R = .454	R^2 = .206	Adj. R^2 = .202	SE = 8.613
Regression	df = 3	MS = 4374.94	58.972	.000
Residual	df = 683	MS = 74.19	—	—
Total	df = 686	—	—	—

As shown in Table 4, the three predictors together yielded a statistically significant regression model, $F(3, 683) = 58.97$, $p < .001$, accounting for approximately 20.6% of the variance in responsible environmental behavior ($R^2 = .206$, adjusted $R^2 = .202$). This indicates that awareness of Green Chemistry principles, represented by its three dimensions, constitutes a significant, though partial, predictor of students' responsible environmental behavior, with the remaining variance likely attributable to other cognitive, attitudinal, and contextual factors not captured within the present model. To determine the relative predictive contribution of each individual dimension, the unstandardized and standardized regression coefficients were examined, as presented in Table 5.

Table 5. Regression Coefficients for the Prediction of Responsible Environmental Behavior from Awareness of Green Chemistry Dimensions

Predictor	B	SE	β	t	Sig.
(Constant)	25.729	1.871	—	13.752	.000
Waste Prevention Concept	.701	.104	.250	6.738	.000
Resource & Energy Efficiency	.461	.085	.202	5.451	.000
Safety & Degradability	.432	.104	.156	4.164	.000

As shown in Table 5, all three dimensions of awareness of Green Chemistry principles emerged as statistically significant, independent predictors of responsible environmental behavior ($p < .001$ for each). Waste Prevention Concept made the largest relative contribution to the prediction of responsible environmental behavior (β =

.250), followed by Resource and Energy Efficiency (β = .202) and Safety and Degradability (β = .156). The positive sign of all three coefficients confirms that higher levels of awareness across each dimension of Green Chemistry principles are associated with correspondingly higher levels of responsible environmental behavior among university students. Taken together, the regression findings indicate that fostering students' awareness of waste prevention, resource and energy efficiency, and the safety and degradability of chemical products may serve as an effective avenue for promoting responsible environmental behavior.

Discussion

The findings of the present study indicate that university students possess moderately high levels of awareness of Green Chemistry principles, alongside a comparable tendency toward responsible environmental behavior. The significant positive correlation between the total awareness score and total behavior score suggests that cognitive understanding of waste prevention, resource efficiency, and chemical safety translates, at least partially, into pro-environmental action. Furthermore, the regression results confirm that all three dimensions of awareness significantly and independently predict responsible environmental behavior, with Waste Prevention Concept emerging as the strongest contributor. Collectively, these results support the theoretical premise that domain-specific scientific awareness functions as a meaningful antecedent of sustainable behavior, rather than a purely academic construct disconnected from students' everyday environmental choices and civic participation.

A particularly notable finding is the markedly stronger correlation between the behavioral dimensions themselves (Conscious Consumption, Pollution Prevention, and Positive Participation) and the total behavior score, compared to the more moderate correlations linking awareness dimensions to that same outcome. This pattern suggests that while Green Chemistry awareness contributes meaningfully to behavior, it accounts for only a modest share of the variance (20.6%), implying that other psychological and contextual mechanisms are also strongly at play. Equally striking is that Resource and Energy Efficiency, despite showing the strongest correlation with total awareness, was the weakest behavioral predictor, whereas Waste Prevention Concept, a comparatively narrower dimension, exerted the greatest influence—suggesting that concrete, actionable knowledge translates into behavior more readily than broader technical understanding.

These results are largely consistent with, and extend, prior literature. Santosa et al. (2023) similarly reported a positive association between green chemistry knowledge and students' environmental care behavior, though without disaggregating specific predictive dimensions as the present study does. The moderate, rather than strong, awareness–behavior link mirrors the theoretical caution raised by Kollmuss and Agyeman (2002) and empirically confirmed by Wang and Zhang (2021), who found the attitude–behavior pathway within the Knowledge-Attitude-Behavior model to be comparatively weak. This aligns with Jindal et al. (2025) and Zhang et al. (2024), who emphasized that awareness alone rarely determines behavior without mediating psychological factors, consistent with the Theory of Planned Behavior perspective advanced by Araújo et al. (2025) and Valencia-Arías et al. (2026). Additionally, findings resonate with Chen et al. (2020) and Hurst et al. (2019) regarding green chemistry education fostering systems thinking, and with Husban (2025) and Rohizan et al. (2026) on general environmental awareness predicting sustainable behavior among students.

These findings carry practical implications for higher education institutions, particularly chemistry departments and curriculum designers seeking to strengthen students' environmental responsibility. Given that Waste Prevention Concept was the strongest behavioral predictor, curricula should prioritize concrete, applicable content—such as atom economy and waste minimization—over purely theoretical exposure to green chemistry frameworks. Universities may also benefit from integrating experiential and service-learning components, such as recycling initiatives or sustainability campaigns, that translate awareness into observable civic action. For policymakers, the results support embedding Green Chemistry principles within general education requirements, not solely specialized chemistry programs, given their demonstrated relevance to students' everyday consumption, waste, and participatory behaviors. Ultimately, these implications reinforce the value of awareness-building as one component within a broader, multi-pronged strategy for cultivating environmentally responsible citizens.

Several limitations should be acknowledged when interpreting these findings. First, the cross-sectional design precludes causal inferences regarding the direction of the awareness–behavior relationship. Second, the reliance on self-report measures for both constructs introduces potential social desirability bias, particularly for behavioral items describing socially valued environmental actions. Third, the sample was drawn from a limited number of faculties within a single university, which may restrict the generalizability of findings to students in other disciplines, institutions, or cultural contexts. Fourth, the regression model explained only a modest proportion of variance in responsible environmental behavior, indicating that important psychological, social, or contextual predictors—such as attitudes, subjective norms, or perceived behavioral control—were not captured within the present study's scope.

Future research should address these limitations by employing longitudinal or experimental designs capable of establishing causal pathways between Green Chemistry awareness and environmental behavior over time. Incorporating behavioral observation or objective indicators, alongside self-report measures, would strengthen the validity of findings and reduce reliance on potentially biased self-assessment. Researchers are also encouraged to test integrative models that combine Green Chemistry awareness with established psychological frameworks, such as the Theory of Planned Behavior, to clarify the mediating roles of attitudes and perceived control. Expanding sampling to include diverse disciplines, institutions, and cultural settings would enhance generalizability. Finally, qualitative approaches could usefully explore the lived experiences and motivational processes underlying students' translation of chemical knowledge into sustainable everyday practice.

Conclusion

This study demonstrates that awareness of Green Chemistry principles, encompassing waste prevention, resource and energy efficiency, and chemical safety and degradability, is significantly and positively associated with university students' responsible environmental behavior, accounting for a meaningful, though partial, share of its variance. These findings position Green Chemistry education not merely as a technical or disciplinary pursuit but as a viable pathway toward cultivating environmentally conscious citizens and future professionals. By strengthening students' understanding of waste minimization and safer chemical design, higher education institutions can contribute meaningfully to broader sustainability goals. Nonetheless, given the modest proportion of explained variance, awareness-raising initiatives should be complemented by attitudinal, normative, and structural interventions to more comprehensively foster lasting, responsible environmental engagement among emerging generations.

Funding
The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/2025/01/34544).

Acknowledgments
The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/2025/01/34544).

Conflicts of Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review.

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