INTERNATIONAL JOURNAL OF ENVIRONMENT, ENGINEERING & EDUCATION

ISSN 2656-8039 (ONLINE)
VOLUME 8 • ISSUE 3 • SEPTEMBER 2026

Received: 18 May 2026 | Accepted: 9 September 2026 | Published: 20 September 2026

Research Article

From Environmental Literacy to Sustainable Lifestyle: A Three-Wave CB-SEM Analysis of Virtual Reality Learning Experience among University Students

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ABSTRACT

Universities increasingly require pedagogical approaches that connect environmental literacy with sustainable lifestyle practices. This study examined the associations of environmental knowledge and environmental skills with sustainable lifestyle and assessed potential indirect pathways through a virtual reality (VR) learning experience. The final analytical sample comprised 400 university students who completed all three assessments and met the prespecified data-quality criteria. Environmental knowledge and skills were measured before the session, VR learning experience immediately afterward, and sustainable lifestyle through a self-report follow-up two weeks later. Confirmatory factor analysis and covariance-based structural equation modeling were applied. The model demonstrated acceptable fit (CMIN/DF = 2.376, RMSEA = 0.059, SRMR = 0.052, CFI = 0.936, TLI = 0.927). Environmental knowledge was positively associated with sustainable lifestyle ($\beta = 0.182$, $p < 0.001$) and VR learning experience ($\beta = 0.312$, $p < 0.001$). Environmental skills showed larger standardized associations with sustainable lifestyle ($\beta = 0.241$, $p < 0.001$) and VR learning experience ($\beta = 0.451$, $p < 0.001$). VR learning experience had the largest standardized direct association with sustainable lifestyle ($\beta = 0.373$, $p < 0.001$). The model-implied indirect effects were 0.116 for environmental knowledge and 0.168 for environmental skills and were interpreted descriptively. The model explained 51.4% of the variance in VR learning experience and 68.7% of the variance in sustainable lifestyle. These findings suggest that immersive learning experience may provide an intermediate link between environmental literacy and short-term self-reported sustainable practices. Causal and long-term claims require comparison groups, longer follow-up, and objective behavioral indicators.

KEYWORDS environmental awareness • environmental education • education for sustainable development • ecological concepts • immersive learning • transformative learning • pro-environmental behavior

ARTICLE CITATION
E. S. Sahabuddin, M. Irfan, Syamsuddin, H. Pagarra, A. Makkasau, Sulfasyah, F. F. Ali, "From Environmental Literacy to Sustainable Lifestyle: A Three-Wave CB-SEM Analysis of Virtual Reality Learning Experience among University Students," International Journal of Environment, Engineering and Education, Vol. 8, No. 3, pp. 474-499, 2026. https://doi.org/10.55151/ijeedu.v8i3.535

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1. INTRODUCTION

The transition toward sustainable lifestyles has become a central concern in environmental education because contemporary patterns of consumption, mobility, energy use, product selection, and waste generation contribute to resource depletion, carbon emissions, pollution, and ecological degradation [1]–[3]. A sustainable lifestyle can be defined as a pattern of daily living that minimizes environmental harm while maintaining quality of life and supporting social well-being [4]. This construct is reflected in specific behavioral practices, including reducing unnecessary consumption, conserving energy, limiting single-use products, selecting low-carbon transportation, recycling, repairing and reusing materials, and choosing durable or lower-impact products [5]–[7]. Sustainable lifestyle development is particularly relevant among university students because consumption habits, civic orientations, and professional values established during higher education may influence subsequent environmental decision-making.

Higher education institutions are positioned to develop the competencies required for environmentally responsible decision-making. Education for Sustainable Development emphasizes acquiring knowledge, skills, values, attitudes, and behavioral capacities that enable learners to respond to sustainability challenges [8]. This orientation is consistent with environmental literacy theory, which conceptualizes environmentally responsible behavior as an outcome of ecological understanding, cognitive competence, affective dispositions, and action-oriented capabilities [9], [10]. Within this framework, environmental knowledge and environmental skills constitute distinct but related components. Environmental knowledge refers to an individual's understanding of ecological systems, environmental problems, anthropogenic impacts, and potential solutions. Environmental skills refer to the ability to interpret environmental information, evaluate alternatives, assess trade-offs, solve problems, and formulate feasible courses of action [11]–[14].

The relationship between environmental knowledge and sustainable behavior is not necessarily linear. Previous research indicates that environmental knowledge is associated with pro-environmental behavior but is often insufficient to produce consistent behavioral change [15], [16]. Individuals may understand environmental problems while continuing environmentally harmful practices because of habitual behavior, convenience, perceived financial costs, social norms, inadequate infrastructure, limited perceived behavioral control, or the psychological distance of environmental consequences [17]–[21]. This discrepancy is commonly described as the knowledge–action gap. The gap is particularly relevant to sustainable lifestyle research because many environmental consequences are delayed, spatially distant, cumulative, or difficult to observe directly. Environmental education must therefore extend beyond factual information and provide learning conditions that connect ecological understanding with personal relevance, practical decision-making, and behavioral competence [12], [22].

Environmental skills may reduce the knowledge–action gap by supporting the application of environmental knowledge in everyday decision contexts. Sustainable choices frequently require individuals to evaluate competing considerations, including cost, convenience, comfort, accessibility, environmental impact, and social expectations. Students with stronger environmental skills may be better able to evaluate sustainability claims, identify misleading environmental information, compare behavioral alternatives, and formulate actions that remain feasible under practical constraints. Environmental skills can therefore be understood as behavior-proximal competencies that support translating ecological understanding into specific decisions and recurring sustainable practices.

Immersive learning technologies provide a potential instructional mechanism for strengthening the relationship among environmental knowledge, environmental skills, and behavior. Virtual reality (VR) has received increasing attention in education because complex processes can be represented through immersive, interactive, and experiential simulations [23], [24]. In sustainability education, VR can represent environmental consequences that may otherwise be difficult to observe, including pollution, waste accumulation, deforestation, climate-related impacts, excessive resource consumption, and the cumulative effects of lifestyle choices. Compared with conventional instructional media, VR can provide presence, interactivity, agency, embodiment, and spatial immersion, allowing learners to experience simulated environmental conditions and observe the consequences of specific decisions [25], [26]. These affordances may increase the visibility, contextual relevance, and cognitive accessibility of abstract environmental problems.

The Cognitive Affective Model of Immersive Learning provides a theoretical basis for examining the educational function of VR learning experiences. The model proposes that technological affordances, including presence and agency, influence cognitive and affective processes such as interest, motivation, self-efficacy, embodiment, self-regulation, and cognitive load [27]. Under this perspective, VR is not treated solely as a delivery technology. Its educational effect depends on instructional alignment, task design, meaningful interaction, feedback, and structured reflection. In environmental education, a well-designed VR learning experience may allow students to evaluate simulated situations, make decisions, observe ecological consequences, and relate those consequences to their daily behavior. Such processes may strengthen the application of environmental knowledge and environmental skills to sustainable lifestyle practices. However, VR cannot be assumed to be inherently more effective than non-immersive instructional media.

Inadequate design may increase extraneous cognitive load, produce short-term novelty effects, or fail to generate transfer beyond the simulated environment [28], [29].

Empirical studies indicate that immersive environmental learning is associated with knowledge acquisition, environmental concern, self-efficacy, conservation attitudes, and pro-environmental behavioral intentions [30]–[32]. These findings support the educational relevance of VR but do not fully establish its relationship with enacted sustainable lifestyle practices. Existing research has predominantly examined engagement, motivation, presence, learning achievement, attitudes, or behavioral intention. Comparatively less attention has been directed toward sustainable lifestyle as a multidomain behavioral construct encompassing energy conservation, mobility, consumption reduction, waste avoidance, repair, reuse, and recycling. Behavioral intention and actual or self-reported behavioral enactment should not be treated as equivalent outcomes because favorable intentions may not consistently translate into recurring daily practices.

A second limitation concerns the conceptual treatment of environmental literacy. Previous studies have frequently operationalized environmental literacy as an aggregate construct, although its components may influence behavior through different mechanisms. Environmental knowledge provides the conceptual basis for recognizing environmental problems and possible responses, whereas environmental skills support the evaluation and implementation of specific actions. Treating these dimensions as analytically distinct is necessary to determine whether sustainable lifestyle practices are associated primarily with what students understand, what they can evaluate and perform, or a combination of both components.

The role of VR learning experience as an explanatory mechanism also remains insufficiently examined. Exposure to immersive technology does not necessarily indicate that meaningful learning has occurred. Behavioral relevance may depend on how students perceive, interpret, and internalize the simulated experience. VR learning experience may therefore function as an intervening construct that connects environmental knowledge and environmental skills with sustainable lifestyle behavior. This proposition is consistent with immersive learning theory, which suggests that educational outcomes emerge from interactions among technological affordances, learner perceptions, cognitive processing, affective responses, and instructional design [27]–[29].

This study tests a three-wave CB-SEM model examining the direct associations of environmental knowledge and environmental skills with short-term self-reported sustainable lifestyle, as well as the model-implied indirect pathways through VR learning experience. This model distinguishes the cognitive and applied components of environmental literacy, evaluates VR learning experience as a potential mediating mechanism, and operationalizes sustainable lifestyle as a multidomain behavioral outcome rather than as behavioral intention alone.

2. LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

2.1. Research Model and Integration Theoretical

The proposed research model is grounded primarily in environmental literacy theory and the Cognitive Affective Model of Immersive Learning. Environmental literacy theory provides the conceptual basis for environmental knowledge and environmental skills, whereas the Cognitive Affective Model of Immersive Learning explains the role of VR learning experience in connecting learner characteristics, immersive processes, and behavioral outcomes.

Environmental literacy refers to the integrated capacity to understand ecological systems, analyze environmental issues, evaluate alternative responses, and undertake environmentally responsible action [9], [10]. This theoretical perspective does not define environmental competence solely in terms of factual knowledge. It also incorporates cognitive skills, affective dispositions, decision-making competence, and action-oriented capacity. Within the present model, environmental knowledge and environmental skills are treated as analytically distinct components of environmental literacy.

Environmental knowledge represents students' understanding of ecological systems, environmental problems, anthropogenic impacts, available sustainable actions, and the relative effectiveness of different behavioral alternatives. Environmental skills represent the cognitive and strategic capacity to identify environmental problems, evaluate information, compare behavioral options, assess trade-offs, and formulate feasible sustainability-related actions. The distinction is theoretically relevant because understanding an environmental issue does not necessarily imply the capacity to respond to it effectively.

This conceptualization is consistent with Education for Sustainable Development, which emphasizes the development of knowledge, skills, values, attitudes, and behavioral capacities required to support a sustainable future [37], [38]. Education for Sustainable Development is positioned in this study as a broader educational orientation rather than as the primary explanatory theory. Environmental literacy theory provides the more specific basis for explaining why environmental knowledge and environmental skills may be associated with sustainable lifestyle practices. Knowledge enables students to identify environmental consequences and recognize lower-impact alternatives, whereas skills support the application of such understanding under practical constraints.

The second principal theoretical foundation is the Cognitive Affective Model of Immersive Learning. This model explains learning in immersive environments through interactions among technological affordances, cognitive processing, affective responses, and learner characteristics [39]. Virtual reality affordances, including immersion, presence, agency, embodiment, realism, and interactivity, may influence attention, interest, motivation, self-efficacy, self-regulation, cognitive load, and perceived learning transfer.

Under this framework, VR learning experience is not defined as exposure to immersive technology alone. It refers to students' perceived experience of learning within an immersive environment, including the degree of presence, realism, involvement, interactivity, agency, and perceived relevance of the simulated scenarios to environmental decision-making. This distinction is necessary because the educational effect of VR depends on how learners cognitively and affectively process its technological affordances.

Action competence and the Theory of Planned Behavior are used as supporting theoretical perspectives. Action competence contributes to the conceptualization of environmental skills by emphasizing intentional, reflective, informed, and problem-oriented capacity to act for sustainability [12], [22]. The Theory of Planned Behavior and related environmental behavior theories provide additional support for recognizing that sustainable behavior may be shaped by attitudes, subjective norms, perceived behavioral control, habits, and contextual conditions in addition to environmental knowledge [15].

These supporting perspectives clarify the behavioral complexity of sustainable lifestyle but do not replace the two principal theoretical foundations. Environmental literacy theory explains the cognitive and action-oriented competencies represented by environmental knowledge and environmental skills. The Cognitive Affective Model of Immersive Learning explains how immersive learning processes may make those competencies more concrete, personally relevant, and transferable to daily behavior.

Based on this theoretical integration, environmental knowledge and environmental skills are positioned as exogenous components of environmental literacy. Both constructs are expected to predict sustainable lifestyle directly and to influence how students perceive and process VR-based environmental learning. VR learning experience is positioned as a potential intermediate construct linking environmental literacy with sustainable lifestyle.

2.2. Sustainable Lifestyle as a Behavioral Outcome

Sustainable lifestyle is defined as a pattern of daily behavior that reduces environmental pressure across multiple domains of individual activity. It includes practices related to energy conservation, transportation, consumption, food selection, waste avoidance, product reuse, repair, recycling, and preference for durable or lower-impact products [40], [41]. This construct differs from environmental attitude because it concerns reported behavioral enactment rather than general evaluation, concern, or support for environmental protection.

Within environmental behavior research, sustainable lifestyle practices can be classified as environmentally significant behaviors because they produce direct or indirect consequences for resource use, environmental quality, emissions, and ecosystem sustainability [16], [42]. Some behaviors affect the environment through direct material or energy consumption, whereas others influence environmental outcomes through purchasing patterns, waste management, or product-life extension.

A sustainable lifestyle should be assessed as a multidomain construct. Consistent behavior in one environmental domain does not necessarily indicate comparable behavior in another. For example, an individual may conserve electricity but continue to rely on high-emission transportation. Another individual may separate recyclable waste while maintaining excessive consumption patterns. A single behavioral indicator would therefore provide an incomplete representation of sustainable lifestyle.

The present study conceptualizes sustainable lifestyle through several related behavioral domains: energy conservation, low-carbon mobility, waste avoidance, recycling and repair, and responsible consumption. This multidomain specification is consistent with the General Ecological Behavior framework, which organizes ecological behavior across energy use, mobility, consumption, waste avoidance, recycling, and other forms of environmental action [5], [6].

The adoption of sustainable practices is affected by psychological and structural constraints. Psychological barriers include habit, self-justification, uncertainty regarding environmental impact, perceived insignificance of individual action, and the temporal or spatial distance of environmental consequences [15], [18], [43]. Structural barriers include financial cost, limited access, inadequate infrastructure, restricted availability of alternatives, and socio-material conditions that make environmentally harmful choices easier to perform [44]–[46].

These constraints indicate that sustainable lifestyle cannot be explained by environmental knowledge alone. Behavioral enactment may require the ability to evaluate available alternatives, manage practical trade-offs, and connect environmental consequences with personally relevant decisions. The present study therefore examines environmental knowledge, environmental skills, and VR learning experience as distinct explanatory variables associated with sustainable lifestyle.

2.3. Environmental Literacy

Environmental literacy is generally defined as the capacity to understand environmental systems, evaluate environmental issues, and make informed decisions that support environmentally responsible action [9], [10]. Its conceptual scope includes factual and procedural knowledge, cognitive skills, affective dispositions, behavioral determinants, and environmental action [10]. Within Education for Sustainable Development, environmental literacy is also aligned to develop learners who possess the competencies required to evaluate sustainability problems and select responsible courses of action [47], [48].

The present study focuses on two cognitive and action-oriented components of environmental literacy: environmental knowledge and environmental skills. These components are examined separately because they represent different capacities and may influence sustainable lifestyle through different pathways.

2.3.1. Environmental Knowledge

Environmental knowledge refers to an individual's understanding of ecological concepts, environmental problems, causal relationships between human activity and environmental consequences, and actions that can reduce environmental harm. It provides the cognitive basis for recognizing environmental problems, interpreting their causes, and distinguishing among alternative responses.

Environmental knowledge can be differentiated into system knowledge, action-related knowledge, and effectiveness knowledge [10]. System knowledge concerns the functioning of ecological systems and the causes and consequences of environmental disruption. Action-related knowledge concerns identifying behaviors that may reduce environmental pressure. Effectiveness knowledge concerns the relative environmental impact of different actions.

These forms of knowledge are relevant to sustainable lifestyle because environmentally responsible decision-making requires more than awareness of environmental degradation. Individuals must also understand which actions are available and which alternatives are likely to produce greater environmental benefit. For example, general awareness of carbon emissions does not necessarily enable an individual to compare the relative effects of transportation choices, product durability, energy use, or waste-reduction practices.

Environmental knowledge is therefore treated as a necessary cognitive resource. Its behavioral influence may nevertheless remain limited when knowledge is not accompanied by evaluative competence, perceived behavioral control, supportive infrastructure, or opportunities to apply environmental understanding in realistic contexts.

2.3.2. Environmental Skills

Environmental skills refer to the cognitive and strategic abilities required to identify environmental problems, evaluate evidence, compare alternatives, assess trade-offs, plan actions, and maintain environmentally responsible decisions. These skills extend beyond factual recall because they involve applying environmental understanding to practical situations.

The construct is aligned with action competence for sustainability, which emphasizes the capacity to undertake voluntary, purposeful, informed, and reflective action [49]–[51]. Action competence requires individuals to understand an environmental problem, assess possible responses, perceive some capacity to influence the outcome, and select an appropriate course of action.

Environmental skills are conceptualized as behavior-proximal competencies. Sustainable lifestyle decisions frequently involve competing considerations, including cost, convenience, accessibility, comfort, durability, social expectations, and environmental impact. Individuals with stronger environmental skills may be better able to evaluate environmental claims, detect misleading sustainability information, identify feasible alternatives, and adapt their decisions when barriers arise.

The distinction between environmental knowledge and environmental skills is therefore analytically necessary. Knowledge concerns what individuals understand about environmental systems and sustainable actions—skills concern how that understanding is evaluated, applied, and translated into decisions under actual constraints.

2.4. VR Learning Experience

VR learning experience refers to students' perceived cognitive, affective, and interactive experience during learning in an immersive virtual environment. It includes perceptions of presence, immersion, realism, involvement, interactivity, agency, and the relevance of virtual scenarios to learning objectives and daily environmental behavior.

Virtual reality can represent environmental conditions that are difficult to observe directly because they are spatially distant, temporally delayed, cumulative, or otherwise inaccessible in conventional classroom settings. Simulations may present deforestation, waste accumulation, pollution, temperature change, resource depletion, or the consequences of different consumption and mobility decisions [24], [35], [36].

The educational relevance of VR is explained partly by its capacity to situate learners within an interactive representation of an environmental problem. Presence may increase the perception of being located within the simulated environment. Agency may allow learners to make decisions and observe their consequences. Interactivity may support active exploration rather than passive information reception. Realism and embodiment may make abstract ecological processes easier to interpret.

The Cognitive Affective Model of Immersive Learning indicates that these affordances do not directly guarantee learning outcomes [39]. Their effects depend on cognitive processing, affective engagement, instructional design, learner characteristics, and cognitive load. A visually complex simulation may increase immersion but reduce learning when relevant information is obscured or when the environment imposes excessive processing demands.

VR learning experience is therefore treated as a learner-perceived educational construct rather than as a technological attribute. A meaningful experience is expected to occur when the virtual environment supports interpretation, decision-making, feedback, reflection, and perceived transfer to non-virtual contexts.

2.5. Hypothesis Development

The proposed hypotheses represent three categories of relationships. First, environmental knowledge and environmental skills are expected to predict sustainable lifestyle directly. Second, both environmental literacy components are expected to predict VR learning experience. Third, VR learning experience is expected to predict sustainable lifestyle and mediate the relationships between environmental literacy and sustainable lifestyle.

2.5.1. Environmental Knowledge and Sustainable Lifestyle

Environmental knowledge provides the conceptual basis for recognizing environmental problems, interpreting the consequences of daily activities, and identifying lower-impact alternatives. Individuals who understand the relationships among energy consumption, transportation, product use, waste generation, emissions, and ecological degradation may be better positioned to evaluate their daily routines.

System knowledge allows environmental consequences to be understood. Action-related knowledge identifies possible behavioral responses. Effectiveness knowledge enables comparison of the relative environmental effects of those responses [10], [11]. Together, these forms of knowledge may support decisions concerning energy conservation, low-carbon mobility, responsible consumption, waste avoidance, recycling, repair, and reuse.

The expected relationship should nevertheless be interpreted cautiously. Environmental knowledge does not automatically result in sustainable behavior. Habits, norms, cost, convenience, perceived behavioral control, infrastructure, identity, and efficacy beliefs may weaken the association between knowledge and action [15]–[17]. Knowledge remains relevant because sustainable action requires individuals to recognize environmental consequences and distinguish between behavioral alternatives.

H1: Environmental knowledge has a positive effect on sustainable lifestyle.

2.5.2. Environmental Skills and Sustainable Lifestyle

Environmental skills are expected to have a positive effect on sustainable lifestyle because they involve applying environmental understanding to practical decisions. Sustainable choices commonly require individuals to evaluate trade-offs between price and durability, convenience and environmental impact, immediate comfort and long-term consequences, or established routines and alternative practices.

Individuals with stronger environmental skills may be better able to search for relevant information, evaluate sustainability claims, detect greenwashing, compare alternatives, plan realistic actions, and modify strategies when contextual barriers arise. These capacities may support both the initial selection and subsequent maintenance of sustainable practices.

This reasoning is consistent with action competence, which conceptualizes sustainable action as informed, intentional, reflective, and directed toward feasible change [12], [22], [49]. Environmental skills may therefore contribute more directly to behavioral implementation than declarative knowledge alone.

H2: Environmental skills have a positive effect on sustainable lifestyle.

2.5.3. Environmental Knowledge and VR Learning Experience

Environmental knowledge is expected to influence VR learning experience because prior knowledge shapes the interpretation of new information. In an immersive environmental simulation, students must organize visual, spatial, and interactive stimuli into coherent environmental meaning. Prior ecological understanding may provide the cognitive structure required for this process.

Students with stronger system knowledge may be better able to interpret simulated environmental changes. Students with stronger action-related knowledge may more readily recognize the behavioral alternatives represented within the virtual scenario. Effectiveness knowledge may support evaluation of the relative consequences of different simulated decisions.

Prior knowledge can therefore function as a cognitive scaffold. Without sufficient environmental understanding, an immersive simulation may be perceived as visually engaging but conceptually fragmented. Students with stronger environmental knowledge may be better able to connect virtual representations with ecological processes, environmental consequences, and sustainable action options.

This proposition is compatible with the Cognitive Affective Model of Immersive Learning, in which learner characteristics interact with presence, agency, attention, motivation, and cognitive processing to shape the perceived quality of immersive learning [39].

H3: Environmental knowledge has a positive effect on VR learning experience.

2.5.4. Environmental Skills and VR Learning Experience

Environmental skills are expected to influence VR learning experience because interactive immersive learning requires learners to evaluate conditions, compare alternatives, make decisions, observe feedback, and reflect on consequences. These processes depend partly on problem-solving, critical evaluation, and strategic decision-making abilities.

Students with stronger environmental skills may engage more actively with interactive scenarios. They may be better able to identify the environmental problem represented in the simulation, evaluate available responses, anticipate consequences, and connect virtual feedback with feasible real-world strategies.

From an action-competence perspective, VR may provide a simulated context in which learners can practice environmental decision-making without producing real-world consequences [12], [22]. The instructional value of this practice depends on the learner's capacity to use agency, interpret feedback, and evaluate the implications of alternative actions.

Environmental skills may therefore contribute to a VR learning experience perceived as more meaningful, interactive, reflective, and transferable to daily environmental behavior.

H4: Environmental skills have a positive effect on VR learning experience.

2.5.5. VR Learning Experience and Sustainable Lifestyle

VR learning experience is expected to influence sustainable lifestyle by making environmental consequences more concrete, observable, and personally relevant. Many environmental problems remain psychologically distant because their effects are delayed, geographically dispersed, cumulative, or not immediately visible in everyday life.

Immersive learning may reduce this distance by representing environmental consequences through first-person perspective, visual simulation, interactivity, and cause-and-effect feedback. Students may observe how particular choices affect pollution, waste accumulation, resource use, emissions, or environmental quality. Such representations may support cognitive understanding and behavioral reflection.

Empirical studies indicate that immersive environmental experiences are associated with conservation-related responses, environmental self-efficacy, environmental knowledge, attitudes, and pro-environmental behavioral intentions [26], [30]–[32]. These findings suggest behavioral potential but do not establish that all VR experiences produce sustainable behavior.

The effect of VR is conditional on instructional quality. Simulations that lack clear objectives, meaningful decisions, relevant feedback, or structured reflection may produce novelty responses without facilitating behavioral transfer. Excessive sensory information may also increase extraneous cognitive load [28], [29], [52]. A high-quality VR learning experience is nevertheless expected to support a sustainable lifestyle by increasing perceived relevance, clarifying action–consequence relationships, and facilitating behavioral rehearsal.

H5: VR learning experience has a positive effect on sustainable lifestyle.

2.6. Conceptual Model

The proposed model comprises two exogenous predictors, one intermediate endogenous construct, one behavioral outcome, and one exogenous control variable. Environmental knowledge and environmental skills are specified as the principal predictors. VR learning experience is specified as an intermediate endogenous construct within the structural model. Sustainable lifestyle is specified as the endogenous behavioral outcome.

Environmental knowledge represents understanding of ecological systems, environmental problems, human impacts, sustainable action alternatives, and the relative effectiveness of different actions. Environmental skills represent the capacity to identify problems, evaluate evidence, compare alternatives, manage trade-offs, formulate actions, and maintain sustainable decisions.

VR learning experience represents students' perceptions of presence, realism, involvement, interactivity, agency, and learning relevance during immersive environmental instruction. Its mediating position reflects the proposition that environmental knowledge and environmental skills may become more behaviorally relevant when students interpret environmental consequences through an immersive and interactive learning process.

Environmental attitude is included as a control variable because it is an established affective correlate of environmentally responsible behavior. Environmental psychology and the Theory of Planned Behavior indicate that individuals with more favorable environmental attitudes are generally more likely to support or perform pro-environmental behavior [15]. The present study does not position environmental attitude as a principal explanatory mechanism. It is statistically controlled to determine whether environmental knowledge, environmental skills, and VR learning experience explain variation in sustainable lifestyle beyond students' pre-existing environmental evaluations.

Environmental attitude is therefore specified as an exogenous control variable with a direct path to sustainable lifestyle. The structural effects of environmental knowledge, environmental skills, and VR learning experience are estimated after accounting for environmental attitude. This specification reduces the possibility that the observed associations are attributable solely to general environmental concern.

Figure 1 presents the hypothesized relationships among environmental knowledge, environmental skills, VR learning experience, environmental attitude, and sustainable lifestyle.

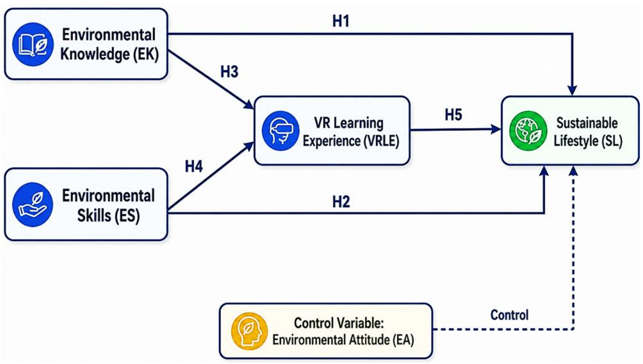

Figure 1. Proposed conceptual model of the hypothesized relationships among the study variables.

The model distinguishes environmental knowledge from environmental skills and specifies two indirect pathways through VR learning experience. The first pathway represents the contextualization of environmental knowledge through immersive learning. The second represents the application and rehearsal of environmental skills within an interactive environmental decision context.

3. MATERIALS AND METHODS

3.1. Research Design

A quantitative, prospective, three-wave, single-group field design was used to examine the hypothesized relationships among environmental knowledge, environmental skills, VR learning experience, and sustainable lifestyle. A standardized immersive virtual reality intervention was administered to all participants. The direct and indirect relationships among the latent constructs were evaluated using covariance-based structural equation modeling (CB-SEM).

The study did not include random assignment, an untreated control group, or a comparison condition using non-immersive instructional media. Environmental knowledge and environmental skills were measured rather than experimentally manipulated. Accordingly, the estimated structural paths were interpreted as temporally ordered associations consistent with the proposed theoretical model, not as definitive causal effects.

Data were collected at three measurement points to establish temporal ordering and reduce the risk of common method variance. Environmental knowledge, environmental skills, environmental attitude, and participant characteristics were measured before the VR intervention at Time 1 (T1). VR learning experience was measured immediately after the intervention at Time 2 (T2). Sustainable lifestyle was measured through a follow-up survey approximately 14 days after the intervention at Time 3 (T3). Temporal separation was used to reduce, but could not eliminate, common-method concerns [53].

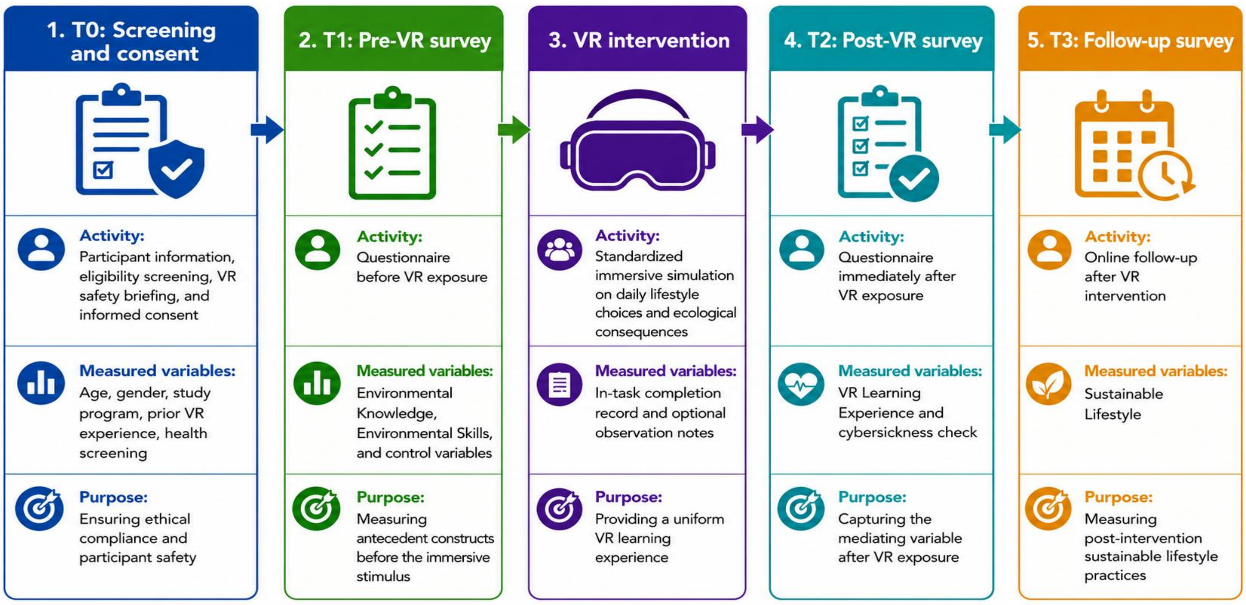

Figure 2. Three-wave data-collection and VR-intervention timeline.

The individual student constituted the unit of analysis. University students were selected because sustainable lifestyle practices are relevant across academic disciplines and because higher education is an institutional context in which environmental competencies, consumption routines, mobility choices, and professional values may be developed. All participants received the same instructional objectives, scenario sequence, facilitator instructions, and measurement schedule.

3.2. Population, Sample, and Sampling Technique

The target population consisted of active university students enrolled in higher education institutions. The accessible population comprised students from participating universities, faculties, and study programs that supported the implementation of the VR-based environmental learning activity. Students from different academic disciplines were included because sustainable lifestyle encompasses behavioral domains that are not restricted to a specific field of study.

Participants were recruited using purposive sampling with quota control. Purposive sampling was selected because participation required respondents to satisfy predetermined eligibility criteria. Quota control was used to improve sample heterogeneity and reduce excessive representation of a single participant category. This procedure did not produce a probability-based or statistically representative sample. The inclusion criteria were as follows:

- active university-student status;
- a minimum age of 18 years;
- voluntary agreement to participate;
- eligibility to use an immersive VR device;
- completion of the T1 questionnaire and VR intervention;
- availability to complete the immediate post-intervention assessment; and
- availability to complete the approximately 14-day follow-up survey.

Participants were excluded before VR exposure when they reported conditions that could increase the risk of adverse reactions to immersive technology. These conditions included severe motion sickness, vestibular disorders, photosensitive epilepsy, serious uncorrected visual impairment, or a history of substantial discomfort during previous VR use [54]–[56].

Cases were excluded from the final CB-SEM dataset when participants discontinued the VR session, did not complete the T2 or T3 questionnaire, failed prespecified attention checks, demonstrated invariant or straight-lining response patterns, or recorded implausibly short questionnaire-completion times. Exclusion decisions were based on predefined safety and data-quality criteria rather than on the direction or magnitude of participant responses.

Recruitment was conducted through classroom announcements, student communication groups, and official faculty or study-program communication channels. Prospective participants received information concerning the study objectives, eligibility requirements, VR procedures, data-collection schedule, potential discomfort, confidentiality, voluntary participation, and right to withdraw. Written or electronically documented informed consent was obtained before data collection.

Quota control considered gender, academic background, previous VR experience, and prior exposure to environmental education. The quotas were used to increase variation within the accessible sample rather than to reproduce the demographic distribution of the broader university-student population [57], [58].

The final analytical sample comprised 400 students who completed all three measurement stages and satisfied the data-quality requirements. This sample size was considered sufficient for CB-SEM because adequacy depends on model complexity, number of latent constructs and indicators, estimation procedure, indicator reliability, and distributional characteristics rather than on a single universal threshold [59], [60]. Because non-probability sampling was applied, generalization should be restricted to students and institutional contexts with characteristics comparable to those represented in the study.

3.3. VR Intervention

3.3.1. Intervention Content

The intervention consisted of a standardized immersive environmental learning session designed to represent relationships between everyday lifestyle decisions and ecological consequences. The virtual environment was presented from a first-person perspective and included three sequential scenarios: (1) household energy use; (2) mobility and consumption choices; and (3) waste management and circular practices.

The intervention emphasized decision-based interaction rather than passive observation. Participants were required to identify environmental problems, select among predefined behavioral alternatives, and observe the consequences of their decisions.

In the household-energy scenario, participants examined common electricity-use practices, including leaving devices active when not in use and selecting appliances with different levels of energy efficiency. Participants selected behavioral alternatives and received immediate feedback concerning their simulated energy impact.

In the mobility-and-consumption scenario, participants compared transportation modes and product options according to their represented environmental consequences. The scenario required participants to evaluate alternatives involving emissions, product durability, resource use, and consumption intensity.

In the waste-management and circular-practice scenario, participants sorted waste and selected among disposal, recycling, reuse, and repair options. Visual changes, concise explanatory messages, and environmental-impact indicators were used to represent the consequences of different choices.

3.3.2. Hardware and Interaction

The intervention was delivered using stand-alone immersive VR headsets equipped with motion-tracking controllers. Participants navigated within a restricted virtual area, selected predefined options, interacted with virtual objects, and observed environmental feedback associated with their decisions.

The intervention was designed with a moderate level of interactivity. Participants could exercise agency within the available decision structure, but they could not freely alter the scenario sequence or create responses outside the predefined behavioral alternatives. This controlled structure was applied to maintain comparability across participants.

The same VR application version, instructional content, scenario order, facilitator script, interaction sequence, and feedback logic were used throughout data collection. Device configuration, headset model, tracking system, and software version should be reported explicitly in the final manuscript to permit procedural replication.

3.3.3. Intervention Duration and Safety Procedure

The immersive exposure lasted approximately 6–9 minutes, excluding orientation, equipment calibration, and post-intervention procedures. Before entering the virtual environment, participants received instructions concerning headset use, controller operation, physical boundaries, potential discomfort, and their right to terminate participation. Facilitators received standardized training in device operation, headset adjustment, controller calibration, hygiene procedures, safety monitoring, and responses to cybersickness. During the intervention, participants were monitored for dizziness, nausea, visual discomfort, anxiety, disorientation, or loss of balance.

Figure 3. Experimental setting for the immersive VR environmental-learning intervention (source: authors, 2026).

Table 1. VR Intervention Protocol

Stage	Duration	Procedure	Interactivity and feedback	Quality control
Orientation	3–5 minutes	Explanation of study procedures, safety requirements, headset use, controller functions, and withdrawal rights.	No VR interaction; standardized verbal instruction.	The same facilitator script was used for all participants.
Equipment calibration	1–2 minutes	Headset adjustment, visual-clarity assessment, controller-response testing, and practice selection.	Participants practiced pointing, selecting, and limited navigation.	Technical problems were recorded before the intervention.
Scenario 1: Energy use	2–3 minutes	Identification of household energy-use practices and selection of lower-impact alternatives.	Interactive appliance and electricity-use decisions with immediate visual feedback.	The same task sequence and decision options were used.
Scenario 2: Mobility and consumption	2–3 minutes	Comparison of transportation modes and product-consumption alternatives.	Interactive selection with feedback on represented environmental consequences.	The same feedback rules were applied to all participants.
Scenario 3: Waste and circular practices	2–3 minutes	Waste sorting and selection of disposal, reduction, reuse, recycling, or repair options.	Object-based interaction with visual representation of waste accumulation or reduction.	Completion, interruption, and discomfort were documented.
Post-VR assessment	3–5 minutes	Headset removal, completion of the VR learning experience instrument, and standardized debriefing.	No additional persuasive environmental instruction was provided.	A neutral debriefing protocol was applied.

3.4. Variables and Operational Definitions

The model comprised four principal latent constructs: environmental knowledge, environmental skills, VR learning experience, and sustainable lifestyle. Environmental knowledge and environmental skills were specified as exogenous predictor variables. VR learning experience is specified as an intermediate endogenous construct within the structural model. Sustainable lifestyle was specified as the endogenous outcome variable.

Environmental attitude was included as an exogenous control variable with a direct structural path to sustainable lifestyle. Participant characteristics, including age, gender, academic background, prior VR experience, and previous environmental-learning exposure, were recorded for sample description and potential sensitivity analysis.

Table 2. Operational Definitions of the Study Variables

Variable	Operational definition	Conceptual dimensions	Measurement
Environmental Knowledge (EK)	Students' self-reported understanding of ecological systems, environmental problems, sustainable action alternatives, and the relative effectiveness of environmental actions.	System knowledge; action-related knowledge; effectiveness knowledge	Five-point agreement scale at T1
Environmental Skills (ES)	Students' self-reported capacity to analyze environmental problems, evaluate information, compare alternatives, assess trade-offs, and plan feasible sustainable actions.	Problem analysis; information evaluation; decision-making; action planning; response to practical barriers.	Five-point agreement scale at T1.
VR Learning Experience (VRLE)	Students perceived quality and educational relevance of the immersive VR experience.	Presence; immersion; involvement; realism; interactivity; agency; perceived learning transfer.	Five-point agreement scale at T2.
Sustainable Lifestyle (SL)	Students' reported frequency or consistency of daily behaviors intended to reduce environmental pressure.	Energy conservation; low-carbon mobility; waste avoidance; responsible consumption; repair, reuse, and recycling.	Five-point behavioral-frequency scale at T3.
Environmental Attitude (EA)	Students' general evaluative orientation toward environmental protection, ecological balance, and the environmental consequences of excessive consumption.	Environmental concern; ecological balance; concern regarding consumption-related impact.	Five-point agreement scale at T1; control variable.

Environmental attitude was controlled because favorable environmental evaluations may influence reported sustainable practices independently of environmental knowledge, environmental skills, or VR learning experience. Its inclusion allowed the principal structural relationships to be estimated after accounting for general pro-environmental orientation. Environmental knowledge was measured through self-report and therefore reflects perceived understanding rather than objectively verified knowledge, while environmental skills represent self-perceived competence rather than directly observed decision-making performance in everyday contexts.

3.5. Research Instruments

The questionnaire adapted established indicators from environmental literacy, immersive learning, presence, action competence, and pro-environmental behavior literature based on their alignment with the operational definitions and measurement model.

Environmental knowledge items were adapted from the three-part environmental knowledge framework comprising system knowledge, action-related knowledge, and effectiveness knowledge [11]. Environmental skills items were adapted from the action-competence for sustainability literature, particularly measures of self-perceived capacity to evaluate environmental problems and formulate feasible actions [12].

VR learning experience items were adapted from immersive-learning and presence research. The indicators represented perceived presence, involvement, realism, interactivity, agency, and transfer of learning from the virtual scenario to everyday environmental decision-making [25], [26], [39].

Sustainable lifestyle items were adapted from the General Ecological Behavior framework and related recommendations for measuring self-reported pro-environmental behavior [5]–[7]. The selected indicators represented behavior across energy conservation, mobility, consumption, waste avoidance, repair, reuse, and recycling. Environmental attitude items were adapted from established environmental-attitude literature and were used only to estimate the control effect on sustainable lifestyle.

Five-point response formats were applied. Environmental knowledge, environmental skills, VR learning experience, and environmental attitude were assessed using an agreement scale ranging from 1 = strongly disagree to 5 = strongly agree. Sustainable lifestyle was assessed using a behavioral-frequency scale ranging from 1 = never to 5 = always.

Table 3. Measurement Structure

Construct	Indicators	Principal adaptation basis	Response format	Indicator coverage
Environmental Knowledge	3	Three forms of environmental knowledge [11].	Five-point agreement scale.	System knowledge, action-related knowledge, and effectiveness knowledge.
Environmental Skills	3	Action competence for sustainability [12].	Five-point agreement scale.	Environmental information evaluation, comparison of alternatives, and action planning.
VR Learning Experience	4	Immersive learning and presence literature [25], [26], [39].	Five-point agreement scale administered after VR exposure.	Presence, involvement, realism, interactivity, agency, and perceived transfer.
Sustainable Lifestyle	4	General Ecological Behavior and pro-environmental behavior literature [5]–[7].	Five-point behavioral-frequency scale administered at follow-up.	Energy, mobility, consumption, waste avoidance, repair, reuse, and recycling.
Environmental Attitude	3	Environmental-attitude literature.	Five-point agreement scale.	Environmental protection, ecological balance, and consumption-related environmental concern.

Note. Complete item wording, item codes, adaptation sources, and scoring procedures should be reported in Supplementary Table S1.

The three environmental knowledge and skills indicators were retained because they represented distinct conceptual dimensions and demonstrated acceptable psychometric performance. Constructs with three indicators were considered adequate when supported by standardized factor loadings, internal consistency, convergent validity, discriminant validity, and overall measurement-model fit.

3.6. Data Collection Procedure

Data collection was conducted offline in classrooms, laboratories, or university learning facilities that provided adequate space and safety for immersive VR use. At T1, participants received study information, completed eligibility screening, provided informed consent, and completed a baseline questionnaire measuring environmental knowledge, environmental skills, environmental attitude, demographic characteristics, prior VR experience, and previous environmental-learning exposure.

Participants then received standardized orientation and completed the immersive VR intervention. Facilitators documented intervention completion, technical interruptions, repeated instructional needs, and adverse symptoms for participant-flow and data-quality reporting. Immediately afterward, participants completed the T2 questionnaire measuring VR learning experience, while cybersickness or discomfort symptoms were recorded for safety monitoring and identification of incomplete exposure.

At T3, approximately 14 days later, participants completed an online follow-up questionnaire measuring sustainable lifestyle. Responses across the three waves were matched using unique study codes rather than direct identifiers. Before analysis, the combined data set was screened for incomplete or duplicate responses, attention-check failures, invariant responding, implausible completion times, and missing data required for the primary model.

3.7. Data Analysis

3.7.1. Preliminary Data Screening

Preliminary analysis included examination of missing data, response distributions, univariate outliers, multivariate outliers, normality, linearity, and multicollinearity. Participant characteristics and construct scores were summarized using frequencies, percentages, means, and standard deviations, as appropriate. Cases that did not satisfy the prespecified completion and response-quality criteria were excluded before estimation of the measurement and structural models. Data-screening decisions were documented to distinguish exclusions related to eligibility, intervention completion, follow-up attrition, and statistical response quality.

3.7.2. Measurement-Model Evaluation

Confirmatory factor analysis was conducted before testing the hypothesized structural paths. Each indicator was specified to load only on its theoretically assigned latent construct, with indicator reliability assessed using standardized factor loadings, internal consistency using composite reliability, convergent validity using factor loadings and average variance extracted, and discriminant validity by comparing relationships among constructs with the variance captured by their indicators. Indicator deletion or correlated residual specification was permitted only when theoretically justified, substantively interpretable, and transparently reported.

3.7.3. Structural-Model Evaluation

The structural model was estimated using maximum likelihood estimation for the theoretically specified latent-variable model and adequate sample size [60], [61].

Direct effects were assessed using standardized coefficients, standard errors, critical ratios, and p-values, with hypotheses supported at $p < 0.05$ in the proposed direction. Environmental attitude was controlled through a direct path to sustainable lifestyle. Indirect effects through VR learning experience were calculated descriptively as potential pathways linking environmental knowledge and skills with sustainable lifestyle.

3.7.4. Model-Fit Assessment

Model fit was assessed using multiple indices because no single statistic provides a sufficient evaluation of model adequacy. The reported indices included chi-square divided by degrees of freedom (CMIN/DF), the root mean square error of approximation (RMSEA), the standardized root mean square residual (SRMR), the comparative fit index (CFI), the Tucker–Lewis's index (TLI), the goodness-of-fit index (GFI), and the adjusted goodness-of-fit index (AGFI).

The model was provisionally considered acceptable when CMIN/DF was below 3.00, RMSEA and SRMR were below 0.08, and CFI and TLI exceeded 0.90 [62]–[66]. These criteria were interpreted collectively rather than as rigid decision rules. GFI and AGFI were reported as supplementary indices because their values are sensitive to sample size and model complexity.

4. RESULTS

4.1. Participant Flow and Respondent Characteristics

4.1.1. Participant Flow

A total of 465 university students were approached, of whom 23 were excluded after eligibility and virtual reality safety screening, leaving 442 eligible participants. Among these, 430 completed the Time 1 assessment, which measured environmental knowledge, environmental skills, environmental attitude, and background characteristics. Eleven participants did not complete the standardized virtual reality exposure, resulting in 419 participants receiving the intervention. At Time 2, 414 participants completed the post-exposure assessment of virtual reality learning experience and cybersickness symptoms.

Nine participants did not complete the two-week follow-up, leaving 405 participants at Time 3. Data screening excluded five responses because of incomplete data, failed attention checks, straight-lining, or implausible completion times. Therefore, the final analytical sample comprised 400 valid responses for confirmatory factor analysis and covariance-based structural equation modeling.

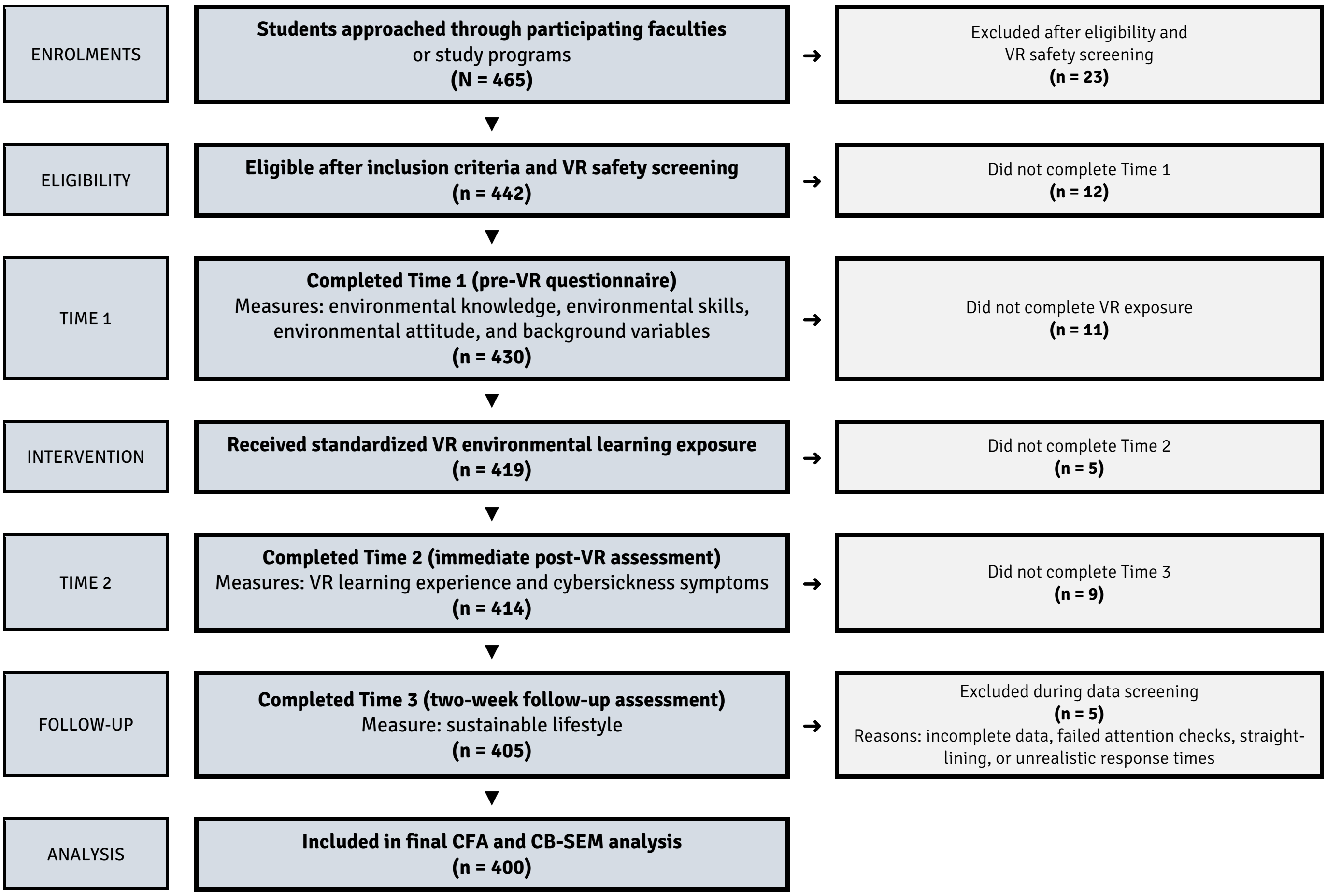

Figure 4. Participant Flow Diagram (CONSORT-Style) for the Three-Wave VR-Based Environmental Learning Study.

4.1.2. Respondent Characteristics

The demographic and background characteristics of the final sample are presented in Table 4. The characteristics examined included gender, age, previous virtual reality experience, and prior exposure to environmental learning.

The final sample consisted of 224 female respondents and 176 male respondents, representing 56.0% and 44.0% of the sample, respectively. Respondents aged 21–23 years constituted the largest age group at 51.25%, followed by respondents aged 18–20 years at 30.3%. Respondents older than 23 years accounted for 18.5% of the sample.

Table 4. Respondent Profile (N=400).

Characteristic	Category	Frequency	Percentage
Gender	Male	176	44.00%
	Female	224	56.00%
Age	18–20 years	121	30.30%
	21–23 years	205	51.25%
	>23 years	74	18.50%
Prior VR experience	Never used VR before	169	42.30%
	Used VR 1–2 times	151	37.75%
	Used VR more than 2 times	80	20.00%
Environmental learning exposure	Low	104	26.00%
	Moderate	199	49.80%
	High	97	24.25%

Previous exposure to virtual reality technology was generally limited. A total of 42.3% of respondents had never used virtual reality, while 37.75% used the technology only once or twice. Respondents who had used virtual reality more than twice represented 20.0% of the sample.

Environmental learning exposure was most frequently classified as moderate, accounting for 49.8% of respondents. Low and high environmental learning exposure were reported by 26.0% and 24.2% of respondents, respectively. These distributions indicate that the analytical sample included respondents with varying levels of prior technological and environmental learning experience.

4.2. Measurement Model Assessment

Confirmatory factor analysis was conducted to determine whether the observed indicators adequately represented their respective latent constructs. The assessment included standardized factor loadings, Cronbach's alpha, composite reliability, and average variance extracted. Standardized factor loadings were used to evaluate indicator reliability, while Cronbach's alpha and composite reliability were used to assess internal consistency. Average variance extracted was examined to determine convergent validity. The measurement model included five latent constructs: environmental knowledge, environmental skills, virtual reality learning experience, sustainable lifestyle, and environmental attitude. The results are shown in Table 5.

Table 5. Measurement Model Assessment.

Construct	Item Code	Standardized Loading	Cronbach's Alpha	CR	AVE
Environmental Knowledge	EK1	0.803	0.863	0.863	0.678
	EK2	0.846			
	EK3	0.821			
Environmental Skills	ES1	0.812	0.873	0.874	0.698
	ES2	0.858			
	ES3	0.835			
VR Learning Experience	VRLE1	0.790	0.899	0.899	0.690
	VRLE2	0.827			
	VRLE3	0.861			
	VRLE4	0.844			
Sustainable Lifestyle	SL1	0.776	0.886	0.887	0.662
	SL2	0.821			

Construct	Item Code	Standardized Loading	Cronbach's Alpha	CR	AVE
	SL3	0.848			
	SL4	0.807			
Environmental Attitude	EA1	0.781	0.850	0.851	0.655
	EA2	0.835			
	EA3	0.811			

The standardized factor loadings ranged from 0.776 to 0.861. All loadings exceeded the minimum criterion of 0.50 and the preferred criterion of 0.70, indicating that each indicator had an adequate association with its designated latent construct [60], [63].

Cronbach's alpha values ranged from 0.850 to 0.899, while composite reliability values ranged from 0.851 to 0.899. Each value exceeded the recommended threshold of 0.70, indicating satisfactory internal consistency across the five constructs [60], [67].

The average variance extracted values ranged from 0.655 to 0.698. These values exceeded the minimum criterion of 0.50, indicating that each construct explained more than half of the variance in its corresponding indicators [67]. The results therefore supported indicator reliability, internal consistency reliability, and convergent validity.

4.3. Discriminant Validity

Discriminant validity was evaluated using the Fornell–Larcker criterion. Under this criterion, the square root of the average variance extracted for each latent construct was compared with its correlations with the other constructs.

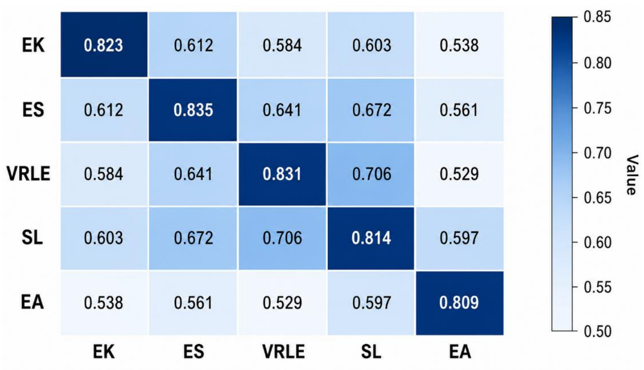

Figure 5. Heatmap of the Fornell–Larcker Criterion for Discriminant Validity Assessment.

The square root of the average variance extracted for each construct exceeded the corresponding inter-construct correlations, as illustrated in Figure 5. This pattern indicates that each construct shared more variance with its own indicators than with indicators representing other constructs.

The findings supported the empirical distinction among environmental knowledge, environmental skills, virtual reality learning experience, sustainable lifestyle, and environmental attitude. The five constructs were therefore retained as separate latent variables in the subsequent structural model.

4.4. Structural Model Fit

Following validation of the measurement model, the structural model was estimated using the maximum likelihood method in IBM AMOS Program. Model fit was evaluated using the normed chi-square, root mean square error of approximation, standardized root mean square residual, comparative fit index, Tucker–Lewis index, goodness-of-fit index, and adjusted goodness-of-fit index. The results are shown in Table 6.

Table 6. Structural Model Fit Indices

Fit Index	Threshold	Result	Interpretation
CMIN/DF	< 3.00	2.376	Acceptable
RMSEA	< 0.08	0.059	Acceptable
SRMR	< 0.08	0.052	Acceptable
CFI	> 0.90	0.936	Acceptable
TLI	> 0.90	0.927	Acceptable
GFI	> 0.90	0.905	Acceptable
AGFI	> 0.80	0.881	Acceptable

The CMIN/DF value of 2.376 was below the maximum criterion of 3.00. The RMSEA and SRMR values were 0.059 and 0.052, respectively, and therefore remained below the recommended upper limit of 0.08.

The incremental fit indices also met their corresponding criteria. The CFI was 0.936, and the TLI was 0.927, with both values exceeding 0.90. The GFI value of 0.905 exceeded the required criterion of 0.90, while the AGFI value of 0.881 exceeded the criterion of 0.80. Collectively, these indices indicated that the structural model demonstrated an acceptable fit to the observed data.

4.5. Direct Effects and Hypothesis Testing

Direct structural relationships were evaluated using standardized regression coefficients, critical ratio values, and probability values. Figure 6 presents the standardized structural model, while Table 7 reports the results of the direct hypothesis tests.

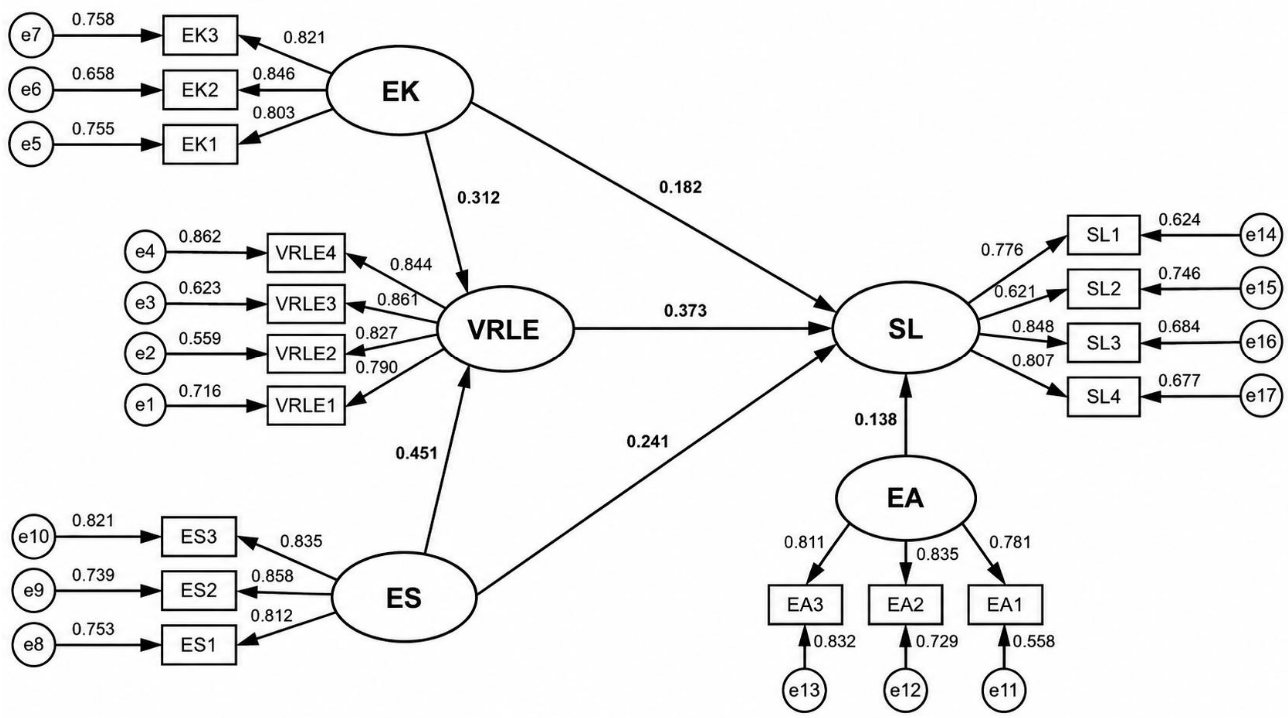

Figure 6. Standardized Structural Model Estimates.

Table 7. Direct Structural Effects and Hypothesis Testing.

Hypothesis	Structural Path			Standardized Estimate	C.R.	p-value	Decision
H1	Environmental Knowledge	→	Sustainable Lifestyle	0.182	3.538	<0.001	Supported
H2	Environmental Skills	→	Sustainable Lifestyle	0.241	4.214	<0.001	Supported
H3	Environmental Knowledge	→	VR Learning Experience	0.312	6.490	<0.001	Supported
H4	Environmental Skills	→	VR Learning Experience	0.451	8.804	<0.001	Supported
H5	VR Learning Experience	→	Sustainable Lifestyle	0.373	6.569	<0.001	Supported
Control	Environmental Attitude	→	Sustainable Lifestyle	0.138	2.809	0.005	Significant

Environmental knowledge and environmental skills were positively associated with sustainable lifestyle. The effect of environmental knowledge was statistically significant ($\beta = 0.182$, C.R. = 3.538, $p < 0.001$), supporting H1, while environmental skills showed a comparatively larger effect ($\beta = 0.241$, C.R. = 4.214, $p < 0.001$), supporting H2. Both constructs were also positively associated with virtual reality learning experience. Environmental knowledge demonstrated a significant effect ($\beta = 0.312$, C.R. = 6.490, $p < 0.001$), supporting H3, whereas environmental skills produced the strongest coefficient among the antecedents of virtual reality learning experience ($\beta = 0.451$, C.R. = 8.804, $p < 0.001$), supporting H4.

Virtual reality learning experience was positively associated with sustainable lifestyle ($\beta = 0.373$, C.R. = 6.569, $p < 0.001$), supporting H5. This coefficient exceeded the direct effects of environmental knowledge and environmental skills on sustainable lifestyle, indicating that the quality of the virtual reality learning experience constituted the strongest direct predictor within the specified model. Environmental attitude, included as a control variable, also showed a positive and statistically significant association with sustainable lifestyle ($\beta = 0.138$, C.R. = 2.809, $p = 0.005$).

The standardized structural coefficients produced model-implied indirect effects through VR learning experience. The indirect effect of environmental knowledge on sustainable lifestyle was 0.116, calculated as the product of the environmental knowledge–VR learning experience path (0.312) and the VR learning experience–sustainable lifestyle path (0.373). The corresponding indirect effect of environmental skills was 0.168, calculated from (0.451×0.373).

The explanatory power of the structural model was evaluated using the squared multiple correlations (R^2) of the endogenous constructs (Table 8). Perceived environmental knowledge and perceived environmental action competence jointly explained 51.4% of the variance in perceived VR learning experience. Perceived environmental knowledge, perceived environmental action competence, perceived VR learning experience, and environmental attitude collectively explained 68.7% of the variance in short-term self-reported sustainable lifestyle.

Table 8. Squared Multiple Correlations for the Endogenous Constructs

Endogenous Construct	Predictors Included in the Model	R^2	Explained Variance
VR Learning Experience	Environmental Knowledge and Environmental Skills	0.514	The predictors explained 51.4% of the variance in VR learning experience.
Sustainable Lifestyle	Environmental Knowledge, Environmental Skills, VR Learning Experience, and Environmental Attitude	0.687	The predictors explained 68.7% of the variance in sustainable lifestyle.

These results indicate that the specified model accounted for a substantial proportion of variance in both endogenous constructs. Nevertheless, the R^2 values represent explanatory associations within a nonrandomized, single-group structural model and should not be interpreted as evidence that VR exposure caused changes in sustainable lifestyle.

5. DISCUSSION

The structural model identified significant temporally ordered associations among environmental knowledge, environmental skills, VR learning experience, environmental attitude, and sustainable lifestyle. VR learning experience showed the strongest standardized association with sustainable lifestyle, followed by environmental skills and environmental knowledge. VR learning experience also statistically mediated the associations of environmental knowledge and environmental skills with sustainable lifestyle.

These findings should be interpreted within the methodological boundaries of the study. All participants received the same VR intervention, and no randomized allocation, untreated control group, or non-VR comparison condition was included. The estimated structural paths therefore indicate associations consistent with the proposed temporal sequence rather than definitive causal effects.

Sustainable lifestyle was assessed through self-reported behavior approximately two weeks after the VR intervention. The outcome consequently represents short-term perceived behavioral enactment rather than objectively verified or sustained environmental behavior. The observed relationships may also reflect social desirability, recall limitations, self-selection, pre-existing environmental orientation, and novelty associated with immersive technology. These limitations do not invalidate the structural associations, but they restrict the strength and duration of the inferences that can be drawn from them.

5.1. Environmental Knowledge and Sustainable Lifestyle

Environmental knowledge was positively associated with sustainable lifestyle. Students who reported stronger understanding of ecological systems, environmental problems, sustainable action alternatives, and the relative effectiveness of environmental actions also reported more frequent sustainability-related practices. This result is consistent with environmental literacy theory, which positions knowledge as a foundational component of environmentally responsible behavior [9], [10].

The finding also supports the distinction among system knowledge, action-related knowledge, and effectiveness knowledge [11]. System knowledge enables students to understand how ecological systems function and how human activities generate environmental consequences. Action-related knowledge identifies behavioral alternatives capable of reducing environmental pressure. Effectiveness knowledge supports comparison of the relative environmental effects of available actions. These forms of knowledge may allow students to evaluate the consequences of energy use, mobility, consumption, and waste-management practices more systematically.

Previous research has similarly indicated that environmental education is associated with improvements in environmental knowledge, attitudes, behavioral intentions, and reported behavior [68]. Environmental knowledge has also been associated with pro-environmental behavior among university students through environmental attitude, environmental sensitivity, and related psychological mechanisms [69]. The present findings are therefore compatible with the proposition that environmental knowledge provides the cognitive basis for recognizing unsustainable practices and identifying lower-impact alternatives.

The standardized association between environmental knowledge and sustainable lifestyle was smaller than the corresponding associations for environmental skills and VR learning experience. This pattern indicates that environmental understanding alone may not be sufficient to support consistent behavioral enactment. The interpretation is consistent with research on the knowledge–action and value–action gaps, which shows that environmentally informed individuals may continue unsustainable practices because of habits, cost, convenience, limited perceived control, weak social norms, inadequate infrastructure, or restricted access to feasible alternatives [70]–[73].

Environmental knowledge may also influence behavior indirectly through perceived responsibility, psychological commitment, private-sphere pro-environmental behavior, and institutional support [74], [75]. Knowledge should therefore be treated as a necessary cognitive resource rather than as a complete explanation of sustainable lifestyle.

This qualification is particularly relevant because sustainable lifestyle encompasses multiple behavioral domains. Energy conservation, low-carbon mobility, waste avoidance, responsible consumption, repair, reuse, and recycling involve different opportunities, constraints, and decision processes [5]–[7]. Meta-analytic evidence indicates that pro-environmental behaviors across different domains are only moderately related, which means that participation in one sustainable practice does not necessarily predict consistent participation in others [76].

Environmental education should consequently emphasize actionable knowledge rather than factual information alone. Students require understanding of environmental processes, available behavioral responses, differences in action effectiveness, and the practical trade-offs associated with implementation. This interpretation is consistent with intervention research indicating that environmental education produces more relevant behavioral outcomes when it is theoretically grounded, behaviorally specific, and connected to measurable practices [77].

5.2. Environmental Skills and Sustainable Lifestyle

Environmental skills showed a stronger direct association with sustainable lifestyle than environmental knowledge. This result suggests that action-oriented competence is more closely connected to behavioral implementation than conceptual understanding alone.

Environmental skills include the capacity to identify environmental problems, evaluate information, compare alternatives, assess trade-offs, plan feasible responses, and maintain decisions under practical constraints. These competencies are required because sustainable lifestyle practices are rarely implemented under ideal conditions. Decisions concerning transportation, product selection, energy use, waste prevention, repair, and reuse are commonly shaped by price, convenience, accessibility, time, social expectations, and established routines.

The finding is consistent with the action-competence approach, which conceptualizes learners as informed and reflective participants capable of analyzing sustainability problems, evaluating possible actions, and intentionally influencing individual or collective conditions [22], [78]. It also corresponds with sustainability-competency frameworks that emphasize systems thinking, anticipatory competence, normative evaluation, strategic planning, and interpersonal competence in addition to environmental knowledge [79], [80].

The stronger association of environmental skills with sustainable lifestyle is also compatible with broader models of pro-environmental behavior. Such models indicate that behavioral enactment depends not only on knowledge or attitude but also on perceived behavioral control, intentions, norms, efficacy, and practical feasibility [16], [17]. Students may understand that a specific behavior is environmentally preferable but remain unable to implement it when they cannot assess available alternatives or manage competing constraints.

Critical evaluation is especially relevant in contemporary consumption contexts. Sustainability claims may differ substantially in validity, specificity, and environmental significance. Students require environmental skills to evaluate product information, identify potentially misleading claims, compare durability and lifecycle effects, and distinguish substantive environmental performance from greenwashing. Research on greenwashing education similarly emphasizes critical environmental literacy as a mechanism for evaluating sustainability-related information [81].

The findings therefore support an educational approach that combines conceptual instruction with applied decision-making. Sustainability education should include problem analysis, comparison of behavioral scenarios, evaluation of environmental claims, decision-making under resource constraints, and preparation of feasible action plans. Intervention evidence indicates that pro-environmental behavior is more likely to improve when educational activities are linked to specific practices and behavioral mechanisms [77].

Environmental skills can consequently be understood as a behavior-proximal component of environmental literacy. Knowledge establishes what students understand about environmental problems and possible solutions. Skills influence how that understanding is evaluated and applied in situations involving uncertainty, competing priorities, and implementation barriers.

5.3. Environmental Literacy as an Antecedent of VR Learning Experience

Environmental knowledge and environmental skills were positively associated with VR learning experience. This finding indicates that the perceived quality of immersive learning was shaped not only by the technological features of the virtual environment but also by learners' prior cognitive and action-oriented capacities.

Environmental knowledge may function as a cognitive scaffold during immersive learning. VR environments present visual, auditory, spatial, and interactive information simultaneously. Students require prior conceptual structures to organize these stimuli and connect simulated events with ecological systems, environmental consequences, and sustainable action alternatives. Without sufficient environmental knowledge, an immersive simulation may be perceived as engaging while remaining conceptually fragmented.

This interpretation positions VR as an experiential extension of conceptual learning rather than as a substitute for prior instruction [24], [39], [82]. Students who understand causal relationships among consumption, energy use, transportation, waste, emissions, and ecological degradation may be better able to interpret the meaning of virtual environmental changes and feedback.

Environmental skills showed a stronger association with VR learning experience than environmental knowledge. This pattern suggests that evaluative and decision-making competence may increase students' capacity to use the interactive affordances of VR. Students with stronger environmental skills may be more capable of comparing simulated alternatives, interpreting feedback, observing action–consequence relationships, and reflecting on the transferability of virtual decisions to everyday behavior.

The result is consistent with the Cognitive Affective Model of Immersive Learning, which proposes that technological affordances influence learning through cognitive and affective processes, including attention, motivation, interest, self-efficacy, embodiment, cognitive load, agency, and self-regulation [39]. Immersion and interactivity may facilitate learning through presence and agency, whereas excessive cognitive load may disrupt attention and reduce perceived presence [83].

Systematic reviews have indicated that immersive VR can support learning outcomes, but its effectiveness varies according to instructional design, interaction quality, task structure, theoretical alignment, and learner characteristics [23], [24]. The present results suggest that environmental literacy constitutes one component of learner readiness. Students may derive greater educational value from immersive simulations when they possess the conceptual and strategic competencies required to interpret environmental information and evaluate interactive choices.

This finding supports the inclusion of structured preparation before VR-based sustainability instruction. Pre-intervention activities may activate relevant ecological concepts, clarify action–effect relationships, and introduce the decision criteria required within the simulation. Such preparation may reduce unnecessary cognitive demands and support more coherent interpretation of immersive content.

5.4. VR Learning Experience and Sustainable Lifestyle

VR learning experience was positively associated with sustainable lifestyle at the two-week follow-up. Students who perceived the VR session as more immersive, realistic, interactive, relevant, and transferable also reported more frequent sustainable lifestyle practices.

The finding is consistent with the Cognitive Affective Model of Immersive Learning, which explains that immersive learning may operate through presence, agency, motivation, self-efficacy, embodiment, self-regulation, and cognitive load [83]. It also corresponds with environmental VR research indicating that immersive or embodied experiences may support environmental learning, conservation-related responses, response efficacy, environmental self-efficacy, and pro-environmental behavioral intentions [30]–[32], [84], [85].

Several mechanisms may explain the observed association. Immersive scenarios can represent environmental consequences that are otherwise delayed, spatially distant, cumulative, or difficult to observe. Visual and interactive feedback may clarify relationships between individual decisions and environmental outcomes. Agency may allow students to compare behavioral alternatives and observe the simulated consequences of their choices. Perceived realism and presence may increase the personal relevance of the represented environmental problem.

The result should not be interpreted as evidence that VR independently caused durable behavioral change. Sustainable lifestyle was measured through self-report, and the follow-up period was limited to approximately two weeks. The finding therefore indicates a short-term statistical association between perceived VR learning quality and reported sustainability-related behavior.

Self-reported environmental behavior may differ from objectively observed behavior and may be affected by measurement error, recall bias, self-presentation, or socially desirable responding [86], [87]. The environmental focus of the intervention may have increased the salience of expected behavior and influenced subsequent reporting [88], [89].

Novelty may also have contributed to the association. Participants with limited prior VR experience may have shown temporarily increased attention, engagement, perceived relevance, or willingness to report sustainable practices because the instructional format was unfamiliar [90]. This possibility is consistent with evidence that immersive technology is not inherently superior to conventional media and may generate distraction or excessive cognitive load when instructional design is inadequate [28], [52].

The significant structural path should therefore be attributed to the perceived quality of the learning experience rather than to VR technology as an isolated medium. Relevant components include presence, interactivity, agency, feedback, reflection, conceptual alignment, and perceived transfer. Because the study did not include a comparison group, no conclusion can be drawn regarding whether immersive VR was more effective than classroom instruction, video-based learning, desktop simulation, or other forms of experiential education.

5.5. Potential Indirect Pathways Through VR Learning Experience

VR learning experience statistically mediated the associations of environmental knowledge and environmental skills with sustainable lifestyle. Students with stronger environmental literacy tended to report a more meaningful immersive learning experience, which was subsequently associated with more frequent self-reported sustainable lifestyle practices.

The findings represent indirect associations within a temporally ordered SEM model. They should not be interpreted as experimental evidence that VR caused behavioral change. The results are nevertheless consistent with experiential learning perspectives, which associate learning with concrete experience, reflection, conceptual interpretation, and application [91]. They are also compatible with the Cognitive Affective Model of Immersive Learning, which explains how presence, agency, motivation, embodiment, self-efficacy, cognitive load, and self-regulation may influence immersive learning outcomes [39], [83].

The indirect pathway from environmental knowledge to sustainable lifestyle through VR learning experience can be interpreted as a process of knowledge concretization. Environmental knowledge may remain abstract when environmental consequences are temporally delayed or not directly observable. VR may represent those consequences as visible, immediate, interactive, and connected to everyday decisions.

Students with stronger prior knowledge may interpret these representations more coherently because they can connect simulated events with ecological concepts, environmental processes, and action–effect relationships. This interpretation is consistent with research indicating that immersive VR may support climate-change learning, environmental awareness, conservation responses, efficacy beliefs, and pro-environmental intentions [84], [85], [92].

The indirect pathway from environmental skills to sustainable lifestyle through VR learning experience can be interpreted as a process of simulated behavioral application. Students with stronger evaluative and decision-making capacities may use VR more effectively as a controlled environment for comparing alternatives, interpreting feedback, observing consequences, and reflecting on potential behavioral transfer [23], [24], [93].

The stronger indirect association involving environmental skills suggests that immersive learning may be particularly relevant when participants possess the competencies required to use interactive scenarios strategically. VR does not independently create environmental competence. Its learning value may depend on participants' capacity to evaluate options and interpret simulated consequences.

Alternative explanations remain possible. Students who completed all three measurement waves may have differed from non-completers in environmental interest, academic motivation, openness to immersive learning, or pre-existing sustainable habits. Environmental attitude was statistically controlled, but unmeasured factors such as environmental identity, peer norms, campus culture, institutional support, and previous behavioral routines may still have influenced both VR learning experience and sustainable lifestyle [16], [17], [94].

VR learning experience should therefore be understood as a plausible complementary mechanism linking environmental literacy with short-term self-reported sustainable lifestyle. The present design does not establish whether this mechanism produces stable behavior beyond the follow-up period.

5.6. Environmental Attitude as a Control Variable

Environmental attitude showed a significant positive association with sustainable lifestyle. Students with more favorable evaluations of environmental protection and ecological balance reported more frequent sustainable practices. This result is consistent with the New Ecological Paradigm and environmental psychology literature, which position attitude as one determinant of pro-environmental behavior alongside values, norms, perceived responsibility, behavioral control, and contextual support [95]–[97].

The standardized association of environmental attitude with sustainable lifestyle was smaller than the corresponding associations for environmental skills and VR learning experience. This pattern indicates that favorable environmental evaluation alone does not fully explain behavioral implementation.

Positive attitudes may fail to translate into sustainable practices when individuals encounter habitual routines, financial costs, inconvenience, limited efficacy, social norms, restricted behavioral control, or inadequate access to sustainable alternatives. This interpretation is consistent with research on the attitude–behavior gap, which emphasizes self-efficacy, perceived effectiveness, trust, institutional support, and feasible behavioral opportunities as conditions that influence whether attitudes are enacted [98]–[101].

Environmental attitude was included as a control variable rather than as a central explanatory construct. Its inclusion allowed the associations of environmental knowledge, environmental skills, and VR learning experience with sustainable lifestyle to be estimated after accounting for students' general pro-environmental orientation.

The principal predictors remained statistically significant after controlling for environmental attitude. This result indicates that their associations with sustainable lifestyle were not reducible to general environmental concern alone. The model therefore supports a differentiated interpretation in which environmental attitude represents evaluative orientation, environmental knowledge represents cognitive understanding, environmental skills represent action capacity, and VR learning experience represents perceived experiential relevance [83], [102], [103].

5.7. Theoretical and Practical Implications

This study provides theoretical and practical implications for environmental literacy, sustainable lifestyle, and immersive learning research. Theoretically, it advances environmental literacy literature by distinguishing environmental knowledge and environmental skills as separate predictors of sustainable lifestyle. The findings show that knowledge supports conceptual understanding, while skills are more directly linked to behavioral implementation. The study also strengthens sustainable lifestyle research by treating sustainable lifestyle as a multidomain behavioral outcome covering energy saving, low-carbon mobility, waste avoidance, responsible consumption, repair, reuse, and recycling, consistent with the General Ecological Behavior framework [5], [11].

This study also contributes to immersive learning theory by positioning VR learning experience as a mediating mechanism rather than merely a technological intervention. The findings show that VR helps translate environmental knowledge and skills into sustainable lifestyle practice through presence, agency, realism, interactivity, and perceived transfer [24], [39]. By integrating environmental literacy, environmental behavior, Education for Sustainable Development, and immersive learning perspectives, the study demonstrates that sustainable lifestyle is best explained through the combined role of knowledge, skills, attitude, and immersive experiential learning [104] – [106].

Sustainability educators should not use VR as a stand-alone instructional activity. VR-based sustainability learning should be embedded in a structured pedagogical sequence consisting of pre-VR conceptual preparation, decision-based immersive scenarios, guided reflection, and post-VR behavioral tasks. Pre-VR preparation should activate system knowledge, action-related knowledge, and effectiveness knowledge. During VR exposure, students should be required to compare alternatives, observe environmental consequences, and justify their decisions. Post-VR activities should translate simulated decisions into specific behavioral commitments, such as reducing single-use items, monitoring household energy use, or documenting low-carbon mobility choices over a defined period.

5.8. Limitations and Future Research Directions

The interpretation of sustainable lifestyle is limited by the use of self-reported data at a two-week follow-up. Such measures may be affected by social desirability bias, recall bias, self-presentation, and heightened awareness immediately after an intervention. The findings may also be influenced by novelty effects, especially among students with limited prior VR experience, and by self-selection bias among students who were willing to participate in a VR-based environmental learning activity. Although environmental attitude was included as a control variable, pre-existing environmental concern, environmental identity, and prior sustainability habits may still have influenced the observed associations. Future research should employ randomized controlled or quasi-experimental designs, include non-VR comparison groups, extend follow-up periods, and incorporate objective behavioral indicators such as waste-sorting accuracy, transport diaries, energy-use records, recycling participation, purchase behavior, or digital behavior logs.”

6. CONCLUSION

This study provides evidence that environmental skills and perceived VR learning experience are more strongly associated with short-term self-reported sustainable lifestyle than environmental knowledge alone. Its main contribution lies in distinguishing environmental knowledge and environmental skills as separate environmental literacy components and in examining VR learning experience as a potential intermediate construct within a three-wave CB-SEM framework. Because the design did not include random assignments, a non-VR comparison group, or objective behavioral indicators, the findings should be interpreted as temporally ordered associations rather than evidence of sustained behavioral change caused by VR exposure.

The findings should be interpreted within the study's methodological boundaries. The design did not include random assignment or a non-VR control group; the sample was selected through purposive sampling with quota control, and sustainable lifestyle was measured through self-report two weeks after the intervention. Therefore, the results do not establish that VR independently produced objective or sustained behavioral change. Future research should use comparison groups, longer follow-up periods, broader sampling strategies, and objective behavioral indicators to examine whether VR-based sustainability learning is associated with stable behavioral outcomes over time.

ACKNOWLEDGMENTS

The authors would like to express their deepest gratitude to the Institute for Research and Community Service (LPPM) Universitas Negeri Makassar, participants and colleagues for their exceptional support and resources, which were critical in facilitating this research.

CONFLICTS OF INTEREST

The authors declare that no conflicts of interest are associated with this study. All aspects of the research were conducted with the utmost integrity and transparency.

DATA AVAILABILITY

The datasets utilized and analyzed during this research are available from the corresponding author upon reasonable request.

ETHICAL STATEMENTS

The authors confirm that the study complied with all applicable local laws, ethical standards, and institutional guidelines, including obtaining approval from relevant ethics committees.

FUNDING

This research was supported by the Central Non-Tax State Revenue (PNBP) Research Program (Grant No. 558/DST/UN36/HK/2026). The funder supported the research and publication.

REFERENCES

[1] T. Jackson, "Motivating Sustainable Consumption," A Rev. Evid. Consum. Behav. Behav. Chang. A Rep. to Sustain. Dev. Res. Netw. as part ESRC Sustain. Technol. Program. Cent. Environ. Strateg. Univ. Surrey Guildf., vol. 15, no. January, pp. 1027–1051, 2005, https://doi.org/10.1260/0958305043026573

[2] S. Lorek and D. Fuchs, "Strong sustainable consumption governance–precondition for a degrowth path?," J. Clean. Prod., vol. 38, pp. 36–43, 2013. https://doi.org/10.1016/j.jclepro.2011.08.00

[3] P. C. Stern, "Toward a coherent theory of environmentally significant behavior," J. Soc. Issues, vol. 56, no. 3, pp. 407–424, 2000, https://doi.org/10.1111/0022-4537.00175

[4] S. Barr, "Sustainable Lifestyles," Environ. Soc., pp. 177–206, 2020, https://doi.org/10.4324/9781315579986-16

[5] F. G. Kaiser, "A general measure of ecological behavior," J. Appl. Soc. Psychol., vol. 28, no. 5, pp. 395–422, 1998, https://doi.org/10.1111/j.1559-1816.1998.tb01712.x

[6] F. G. Kaiser and M. Wilson, "Goal-directed conservation behavior: The specific composition of a general performance," Pers. Individ. Dif., vol. 36, no. 7, pp. 1531–1544, 2004, https://doi.org/10.1016/j.paid.2003.06.003

[7] F. Lange and S. Dewitte, "Measuring pro-environmental behavior: Review and recommendations," J. Environ. Psychol., vol. 63, pp. 92–100, 2019, https://doi.org/10.1016/j.jenvp.2019.04.009

[8] UNESCO, Shaping the Future We Want UN Decade of Education for Sustainable Development. 2005-2014 Final Report. Paris: UNESCO, 2014. [Online]. Available: http://unesdoc.unesco.org/images/0023/002301/230171e.pdf

[9] K. S. Hollweg, J. R. Taylor, R. W. Bybee, T. J. Marcinkowski, W. C. McBeth, and P. Zoido, "Developing a framework for assessing environmental literacy," vol. 122. North American Association for Environmental Education, Washington, DC, 2011. [Online]. Available: http://www.naaee.net/framework

[10] C. E. Roth, Environmental Literacy: Its Roots, Evolution and Directions in the 1990s. Columbus: ERIC/CSMEE Publications, 1992. https://eric.ed.gov/?id=ED348235

[11] J. Frick, F. G. Kaiser, and M. Wilson, "Environmental knowledge and conservation behavior: Exploring prevalence and structure in a representative sample," Pers. Individ. Dif., vol. 37, no. 8, pp. 1597–1613, 2004, https://doi.org/10.1016/j.paid.2004.02.015

[12] D. Olsson, N. Gericke, W. Sass, and J. Boeve-de Pauw, "Self-perceived action competence for sustainability: the theoretical grounding and empirical validation of a novel research instrument," Environ. Educ. Res., vol. 26, no. 5, pp. 742–760, 2020, https://doi.org/10.1080/13504622.2020.1736991

[13] A. Wiek, L. Withycombe, and C. L. Redman, "Key competencies in sustainability: A reference framework for academic program development," Sustain. Sci., vol. 6, no. 2, pp. 203–218, 2011, https://doi.org/10.1007/s11625-011-0132-6

[14] K. Brundiers et al., "Key competencies in sustainability in higher education—toward an agreed-upon reference framework," Sustain. Sci., vol. 16, no. 1, pp. 13–29, 2021, https://doi.org/10.1007/s11625-020-00838-2

[15] A. Kollmuss and J. Agyeman, "Mind the Gap: Why do people act environmentally and what are the barriers to pro-environmental behavior?," Environ. Educ. Res., vol. 8, no. 3, pp. 239–260, 2002, https://doi.org/10.1080/13504620220145401

[16] L. Steg and C. Vlek, "Encouraging pro-environmental behaviour: An integrative review and research agenda," J. Environ. Psychol., vol. 29, no. 3, pp. 309–317, 2009, https://doi.org/10.1016/j.jenvp.2008.10.004

[17] S. Bamberg and G. Möser, "Twenty years after Hines, Hungerford, and Tomera: A new meta-analysis of psycho-social determinants of pro-environmental behaviour," J. Environ. Psychol., vol. 27, no. 1, pp. 14–25, 2007, https://doi.org/10.1016/j.jenvp.2006.12.002

[18] R. Gifford, "The Dragons of Inaction: Psychological Barriers That Limit Climate Change Mitigation and Adaptation," Am. Psychol., vol. 66, no. 4, pp. 290–302, 2011, https://doi.org/10.1037/a0023566

[19] K. T. Stevenson, M. N. Peterson, H. D. Bondell, A. G. Mertig, and S. E. Moore, "Environmental, Institutional, and Demographic Predictors of Environmental Literacy among Middle School Children," PLoS One, vol. 8, no. 3, p. e59519, 2013, https://doi.org/10.1371/journal.pone.0059519

[20] B. Verplanken and W. Wood, "Interventions to break and create consumer habits," J. Public Policy Mark., vol. 25, no. 1, pp. 90–103, 2006, https://doi.org/10.1509/jppm.25.1.90

[21] B. Melovic, S. Rogic, J. C. Smolovic, B. Dudic, and M. Gregus, "The impact of sport sponsorship perceptions and attitudes on purchasing decision of fans as consumers-relevance for promotion of corporate social responsibility and sustainable practices," Sustain., vol. 11, no. 22, p. 6389, 2019, https://doi.org/10.3390/su11226389

[22] F. Mogensen and K. Schnack, "The action competence approach and the 'new' discourses of education for sustainable development, competence and quality criteria," Environ. Educ. Res., vol. 16, no. 1, pp. 59–74, 2010, https://doi.org/10.1080/13504620903504032

[23] D. Hamilton, J. McKechnie, E. Edgerton, and C. Wilson, "Immersive virtual reality as a pedagogical tool in education: a systematic literature review of quantitative learning outcomes and experimental design," J. Comput. Educ., vol. 8, no. 1, pp. 1–32, 2021, https://doi.org/10.1007/s40692-020-00169-2

[24] J. Radianti, T. A. Majchrzak, J. Fromm, and I. Wohlgenannt, "A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda," Comput. Educ., vol. 147, p. 103778, 2020, https://doi.org/10.1016/j.compedu.2019.103778

[25] T. Schubert, F. Friedmann, and H. Regenbrecht, "The experience of presence: Factor analytic insights," Presence Teleoperators Virtual Environ., vol. 10, no. 3, pp. 266–281, 2001, https://doi.org/10.1162/105474601300343603

[26] B. G. Witmer and M. J. Singer, "Measuring presence in virtual environments: A presence questionnaire," Presence, vol. 7, no. 3, pp. 225–240, 1998.

[27] G. Makransky and G. B. Petersen, "Immersive virtual reality and learning," Learn. Instr., vol. 80, no. 4, p. 101509, 2022, https://doi.org/10.1016/j.learninstruc.2022.101509

[28] J. Parong and R. E. Mayer, "Cognitive and affective processes for learning science in immersive virtual reality," J. Comput. Assist. Learn., vol. 37, no. 1, pp. 226–241, 2021, https://doi.org/10.1111/jcal.12482
[29] E. S. Sahabuddin and A. Makkasau, "Utilization of virtual reality as a learning tool to increase students' pro-environmental behavior at universities: A maximum likelihood estimation approach," Eurasia J. Math. Sci. Technol. Educ., vol. 20, no. 12, p. em2540, 2024, https://doi.org/10.29333/ejmste/15654
[30] S. J. Ahn, J. N. Bailenson, and D. Park, "Short- and long-term effects of embodied experiences in immersive virtual environments on environmental locus of control and behavior," Comput. Human Behav., vol. 39, pp. 235–245, 2014, https://doi.org/10.1016/j.chb.2014.07.025
[31] D. M. Markowitz, R. Laha, B. P. Perone, R. D. Pea, and J. N. Bailenson, "Immersive Virtual Reality field trips facilitate learning about climate change," Front. Psychol., vol. 9, no. NOV, p. 2364, 2018, https://doi.org/10.3389/fpsyg.2018.02364
[32] D. Pimentel and S. Kalyanaraman, "The effects of embodying wildlife in virtual reality on conservation behaviors," Sci. Rep., vol. 12, no. 1, p. 6439, 2022, https://doi.org/10.1038/s41598-022-10268-y
[33] R. B. Stevenson, M. Brody, J. Dillon, and A. E. J. Wals, International handbook of research on environmental education. Routledge New York, 2013. https://doi.org/10.4324/9780203813331
[34] F. D. Pertiwi et al., "A New Approach to Measuring Institutional and Researcher Contributions to the SDGs: Combining Data from Elsevier SciVal and VOSviewer," Adv. Sustain. Sci. Eng. Technol., vol. 6, no. 4, 2024, https://doi.org/10.26877/asset.v6i4.1076
[35] G. Makransky, T. S. Terkildsen, and R. E. Mayer, "Adding immersive virtual reality to a science lab simulation causes more presence but less learning," Learn. Instr., vol. 60, pp. 225–236, 2019, https://doi.org/10.1016/j.learninstruc.2017.12.007
[36] R. R. Putra, I. D. Perwitasari, D. M. Rangkuty, V. Tasril, S. Handayani, and A. S. Dewi, "From Virtual To Reality: How Metaverse and VR Technologies Influence Travel Decisions," J. Appl. Eng. Technol. Sci., vol. 6, no. 2, pp. 862–873, 2025, https://doi.org/10.37385/jaets.v6i2.6314
[37] A. V. Agbedahin, "Sustainable development, Education for Sustainable Development, and the 2030 Agenda for Sustainable Development: Emergence, efficacy, eminence, and future," Sustain. Dev., vol. 27, no. 4, pp. 669–680, 2019, https://doi.org/10.1002/sd.1931
[38] H. Kopnina, "Education for the future? Critical evaluation of education for sustainable development goals," J. Environ. Educ., vol. 51, no. 4, pp. 280–291, 2020, https://doi.org/10.1080/00958964.2019.1710444
[39] G. Makransky and G. B. Petersen, "The Cognitive Affective Model of Immersive Learning (CAMIL): a Theoretical Research-Based Model of Learning in Immersive Virtual Reality," Educ. Psychol. Rev., vol. 33, no. 3, pp. 937–958, 2021, https://doi.org/10.1007/s10648-020-09586-2
[40] C. Arias, J. B. Cadena Lozano, and M. A. Bello Bernal, "The Role of Value in Extending the Lifetime of Products: An Analysis of Perceived Value and Green Consumption Values on Pro-Circular Behaviors of Repair and Reuse," Sustain., vol. 16, no. 4, p. 1567, 2024, https://doi.org/10.3390/su16041567
[41] B. Borusiak, A. Szymkowiak, E. Horska, N. Raszka, and E. Zelichowska, "Towards building sustainable consumption: A study of second-hand buying intentions," Sustain., vol. 12, no. 3, p. 875, 2020, https://doi.org/10.3390/su12030875
[42] B. Gatersleben, L. Steg, and C. Vlek, "Measurement and determinants of environmentally significant consumer behavior," Environ. Behav., vol. 34, no. 3, pp. 335–362, 2002, https://doi.org/10.1177/0013916502034003004
[43] T. Marcinkowski and A. Reid, "Reviews of research on the attitude–behavior relationship and their implications for future environmental education research," Environmental Education Research, vol. 25, no. 4. Taylor & Francis, pp. 459–471, 2019. https://doi.org/10.1080/13504622.2019.1634237
[44] E. Shove, "Beyond the ABC: Climate change policy and theories of social change," Environ. Plan. A, vol. 42, no. 6, pp. 1273–1285, 2010, https://doi.org/10.1068/a42282
[45] F. Creutzig, B. Fernandez, H. Haberl, R. Khosla, Y. Mulugetta, and K. C. Seto, "Beyond Technology: Demand-Side Solutions for Climate Change Mitigation," Annu. Rev. Environ. Resour., vol. 41, no. 1, pp. 173–198, 2016, https://doi.org/10.1146/annurev-environ-110615-085428
[46] L. Steg, "Psychology of Climate Change," Annu. Rev. Psychol., vol. 74, no. 1, pp. 391–421, 2023, https://doi.org/10.1146/annurev-psych-032720-042905
[47] Q. Miao and C. Nduneseokwu, "Advancing Environmental Leadership: Education, Development, and Training," Environ. Leadersh. a VUCA Era, pp. 467–538, 2024, https://doi.org/10.1007/978-981-96-0324-4_10
[48] A. Shutaleva, "Ecological Culture and Critical Thinking: Building of a Sustainable Future," Sustain., vol. 15, no. 18, p. 13492, 2023, https://doi.org/10.3390/su151813492
[49] A. E. Torsdottir, D. Olsson, and A. T. Sinnes, "Developing action competence for sustainability – Do school experiences in influencing society matter?," Glob. Environ. Chang., vol. 86, p. 102840, 2024, https://doi.org/10.1016/j.gloenvcha.2024.102840
[50] I. Oinonen, T. Seppälä, and R. Paloniemi, "How does action competence explain young people's sustainability action?," Environ. Educ. Res., vol. 30, no. 4, pp. 499–518, 2024, https://doi.org/10.1080/13504622.2023.2241675
[51] J. B. de Pauw, N. Gericke, D. Olsson, and T. Berglund, "The effectiveness of education for sustainable development," Sustain., vol. 7, no. 11, pp. 15693–15717, 2015, https://doi.org/10.3390/su71115693
[52] J. Parong and R. E. Mayer, "Learning science in immersive virtual reality," J. Educ. Psychol., vol. 110, no. 6, pp. 785–797, 2018, https://doi.org/10.1037/edu0000241
[53] P. M. Podsakoff, S. B. MacKenzie, J. Y. Lee, and N. P. Podsakoff, "Common Method Biases in Behavioral Research: A Critical Review of the Literature and Recommended Remedies," J. Appl. Psychol., vol. 88, no. 5, pp. 879–903, 2003, https://doi.org/10.1037/0021-9010.88.5.879

[54] S. Campbell et al., "Purposive sampling: complex or simple? Research case examples," J. Res. Nurs., vol. 25, no. 8, pp. 652–661, 2020, https://doi.org/10.1177/1744987120927206

[55] E. Chang, H. T. Kim, and B. Yoo, "Virtual Reality Sickness: A Review of Causes and Measurements," Int. J. Hum. Comput. Interact., vol. 36, no. 17, pp. 1658–1682, 2020, https://doi.org/10.1080/10447318.2020.1778351

[56] A. W. Meade and S. B. Craig, "Identifying careless responses in survey data," Psychol. Methods, vol. 17, no. 3, pp. 437–455, 2012, https://doi.org/10.1037/a0028085

[57] J. Daniel, Sampling Essentials: Practical Guidelines for Making Sampling Choices. Sage publications, 2014. https://doi.org/10.4135/9781452272047

[58] S. Campbell, M. Greenwood, S. Prior, T. Shearer, K. Walkem, S. Young, D. Bywaters, and K. Walker, "Purposive sampling: Complex or simple? Research case examples," J. Res. Nurs., vol. 25, no. 8, pp. 652–661, 2020, https://doi.org/10.1177/1744987120927206

[59] E. J. Wolf, K. M. Harrington, S. L. Clark, and M. W. Miller, "Sample Size Requirements for Structural Equation Models: An Evaluation of Power, Bias, and Solution Propriety," Educ. Psychol. Meas., vol. 73, no. 6, pp. 913–934, 2013, https://doi.org/10.1177/0013164413495237

[60] J. F. Hair, W. C. Black, B. J. Babin, and R. E. Anderson, "Multivariate data analysis," 8th ed. Andover, U.K.: Cengage Learning EMEA, 2019.

[61] B. M. Byrne, Structural equation modeling with Mplus: Basic concepts, applications, and programming. routledge, 2013. https://doi.org/10.4324/9780203807644

[62] L. T. Hu and P. M. Bentler, "Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives," Struct. Equ. Model., vol. 6, no. 1, pp. 1–55, 1999, https://doi.org/10.1080/10705519909540118

[63] R. B. Kline, Principles and practice of structural equation modeling. New York, NY, USA: Guilford publications, 2023.

[64] R. E. Schumacker and R. G. Lomax, A Beginner's Guide to Structural Equation Modeling. Oxfordshire, United Kingdom: psychology press, 2004. https://doi.org/10.4324/9781410610904

[65] R. Hoyle and A. T. Panter, "Writing about structural equation models," Struct. Equ. Model. Concepts, issues, Appl., Thousand Oaks, CA, USA: Sage Publications. pp. 158–176, 1995.

[66] S. A. Mulaik, L. R. James, J. Van Alstine, N. Bennett, S. Lind, and C. D. Stilwell, "Evaluation of Goodness-of-Fit Indices for Structural Equation Models," Psychol. Bull., vol. 105, no. 3, pp. 430–445, 1989, https://doi.org/10.1037/0033-2909.105.3.430

[67] C. Fornell and D. F. Larcker, "Evaluating Structural Equation Models with Unobservable Variables and Measurement Error," J. Mark. Res., vol. 18, no. 1, p. 39, 1981, https://doi.org/10.2307/3151312

[68] J. van de Wetering, P. Leijten, J. Spitzer, and S. Thomaes, "Does environmental education benefit environmental outcomes in children and adolescents? A meta-analysis," J. Environ. Psychol., vol. 81, p. 101782, 2022, https://doi.org/10.1016/j.jenvp.2022.101782

[69] M. Mago, M. Yadav, S. Sharma, and H. Kaur, "Environmental knowledge influencing pro-environmental behavior among university students: a serial mediation and MGA approach," Int. J. Sustain. High. Educ., vol. 26, no. 5, pp. 1072–1095, 2025, https://doi.org/10.1108/IJSHE-02-2024-0110

[70] R. Portus et al., "Exploring environmental value action gap and education research: a semi-systematic literature review," Environ. Educ. Res., vol. 30, no. 6, pp. 833–863, 2024 https://doi.org/10.1080/13504622.2024.2314060

[71] C. Neves, T. Oliveira, and F. Santini, "Understanding the determinants of sustainable consumption behavior: Insights from a meta and weight analysis," J. Environ. Manage., vol. 393, p. 126932, 2025, https://doi.org/10.1016/j.jenvman.2025.126932

[72] F. E. Ikuemonisan, Y. O. Kayode, O. O. Popogbe, and O. V. Ikuomenisan, "The role of environmental knowledge, subjective norms, perceived behavioral control, and institutional support in social media advocacy for geoscience-informed sustainability practices," Discov. Sustain., vol. 6, no. 1, 2025, https://doi.org/10.1007/s43621-025-01911-5

[73] A. Dioba, V. Kroker, S. Dewitte, and F. Lange, "Barriers to Pro-Environmental Behavior Change: A Review of Qualitative Research," Sustain., vol. 16, no. 20, p. 8776, 2024, https://doi.org/10.3390/su16208776

[74] X. Yao, Y. Liu, and G. Qi, "Enhancing sustainable consumer practices: the role of environmental knowledge in adopting BORS services," Asia Pacific J. Mark. Logist., vol. 37, no. 7, pp. 1937–1954, 2025, https://doi.org/10.1108/APJML-05-2024-0649

[75] A. K. Trinh, M. D. Tran, and S. Adomako, "Environmental Knowledge and Sustainable Consumption Behavior: Evidence From Vietnam," Sustain. Dev., vol. 33, no. S1, pp. 577–593, 2025, https://doi.org/10.1002/sd.70013

[76] A.-B. Ciocîrlan, H. Baird, and R. Rowe, "A systematic review and meta-analysis of the relationships between pro-environmental behaviours," J. Environ. Psychol., vol. 108, Art. no. 102807, 2025. https://doi.org/10.1016/j.jenvp.2025.102807

[77] W. Świątkowski, F. L. Surret, J. Henry, C. Buchs, E. P. Visintin, and F. Butera, "Interventions promoting pro-environmental behaviors in children: A meta-analysis and a research agenda," J. Environ. Psychol., vol. 96, p. 102295, 2024, https://doi.org/10.1016/j.jenvp.2024.102295

[78] B. B. Jensen and K. Schnack, "The action competence approach in environmental education," Environ. Educ. Res., vol. 3, no. 2, pp. 163–178, 1997, https://doi.org/10.1080/1350462970030205

[79] A. Redman, A. Wiek, and M. Barth, "Current practice of assessing students' sustainability competencies: a review of tools," Sustain. Sci., vol. 16, no. 1, pp. 117–135, 2021, https://doi.org/10.1007/s11625-020-00855-1

[80] P. Sá, M. Lourenço, and V. Carlos, "Sustainability Competencies in Higher Education Research: An Analysis of Doctoral Theses in Portugal," Eur. J. Investig. Heal. Psychol. Educ., vol. 12, no. 4, pp. 387–399, 2022, https://doi.org/10.3390/ejihpe12040028

[81] O. Álvarez-García and J. Sureda-Negre, "Greenwashing and education: An evidence-based approach," J. Environ. Educ., vol. 54, no. 4, pp. 265–277, 2023. https://doi.org/10.1080/00958964.2023.2238190

[82] D. Irfan et al., “Exploring the Effectiveness of VR-Based Educational Games in Improving Student Engagement and Comprehension in Computer Architecture,” J. Appl. Eng. Technol. Sci., vol. 6, no. 2, pp. 1312–1323, 2025, https://doi.org/10.37385/jaets.v6i2.7070

[83] G. B. Petersen, G. Petkakis, and G. Makransky, “A study of how immersion and interactivity drive VR learning,” Comput. Educ., vol. 179, p. 104429, 2022, https://doi.org/10.1016/j.compedu.2021.104429

[84] V. Aksel Stenberdt and G. Makransky, “Mastery experiences in immersive virtual reality promote pro-environmental waste-sorting behavior,” Comput. Educ., vol. 198, p. 104760, 2023, https://doi.org/10.1016/j.compedu.2023.104760

[85] H. Sungur, Z. M. C. van Berlo, H. Hegyiová, and T. Hartmann, “Designing effective VR experiences for pro-environmental outcomes: Enhancing self-efficacy through mastering solutions,” Comput. Hum. Behav. Reports, vol. 19, p. 100783, 2025, https://doi.org/10.1016/j.chbr.2025.100783

[86] C. Kormos and R. Gifford, “The validity of self-report measures of proenvironmental behavior: A meta-analytic review,” J. Environ. Psychol., vol. 40, pp. 359–371, 2014, https://doi.org/10.1016/j.jenvp.2014.09.003

[87] K. Koller, P. K. Pankowska, and C. Brick, “Identifying bias in pro-environmental behavior,” Curr. Res. Ecol. Soc. Psychol., vol. 4, Art. no. 100087, 2023. https://doi.org/10.1016/j.cresp.2022.100087

[88] S. Vesely and C. A. Klöckner, “Social Desirability in Environmental Psychology Research: Three Meta-Analyses,” Front. Psychol., vol. 11, p. 1395, 2020, https://doi.org/10.3389/fpsyg.2020.01395

[89] O. Y. Zhu, D. Greene, and S. Dolnicar, “Should the risk of social desirability bias in survey studies be assessed at the level of each pro-environmental behaviour?,” Tour. Manag., vol. 104, p. 104933, 2024, https://doi.org/10.1016/j.tourman.2024.104933

[90] I. Miguel-Alonso, D. Checa, H. Guillen-Sanz, and A. Bustillo, “Evaluation of the novelty effect in immersive Virtual Reality learning experiences,” Virtual Real., vol. 28, no. 1, p. 27, 2024, https://doi.org/10.1007/s10055-023-00926-5

[91] D. A. Kolb, Experiential Learning: Experience as The Source of Learning and Development, no. 1984. FT press, 1984. https://doi.org/10.1016/B978-0-7506-7223-8.50017-4

[92] C. Hurrell, A. Chai, H. Green, and G. Bradley, “Virtual reality facilitates pro-environmental behavioural intentions,” Environ. Educ. Res., vol. 30, no. 10, pp. 1856–1883, 2024, https://doi.org/10.1080/13504622.2024.2342942

[93] M. Hajj-Hassan, R. Chaker, and A. M. Cederqvist, “Environmental Education: A Systematic Review on the Use of Digital Tools for Fostering Sustainability Awareness,” Sustain. , vol. 16, no. 9, p. 3733, 2024, https://doi.org/10.3390/su16093733

[94] I. Ajzen, “The theory of planned behavior,” Handb. Theor. Soc. Psychol. Vol. 1, vol. 50, no. 2, pp. 438–459, 2012, https://doi.org/10.4135/9781446249215.n22

[95] R. E. Dunlap, K. D. Van Liere, A. G. Mertig, and R. E. Jones, “Measuring endorsement of the new ecological paradigm: A revised NEP scale,” J. Soc. Issues, vol. 56, no. 3, pp. 425–442, 2000, https://doi.org/10.1111/0022-4537.00176

[96] H. Tian and X. Liu, “Pro-Environmental Behavior Research: Theoretical Progress and Future Directions,” Int. J. Environ. Res. Public Health, vol. 19, no. 11, p. 6721, 2022, https://doi.org/10.3390/ijerph19116721

[97] T. Phiri and L. Chakauya, “the Influence of a Soccer Event Sponsorship on Consumer Attitudes, Perceptions and Sponsorship Awareness,” Gsj, vol. 11, no. 6, 2023, [Online]. Available: www.globalscientificjournal.com

[98] M. T. Borges-Tiago, A. Almeida, F. G. B. Tiago, and S. M. M. Avelar, “Bridging the innovative Attitude–Behavior Gap: A dual-level analysis,” J. Innov. Knowl., vol. 9, no. 4, p. 100561, 2024, https://doi.org/10.1016/j.jik.2024.100561

[99] D. T. K. Ng, J. K. L. Leung, S. K. W. Chu, and M. S. Qiao, “Conceptualizing AI literacy: An exploratory review,” Comput. Educ. Artif. Intell., vol. 2, p. 100041, 2021, https://doi.org/10.1016/j.caeai.2021.100041

[100] R. A. Fabio, A. Croce, and C. Calabrese, “Bridging the Green Attitude–Behavior Gap,” J. Sustain. Res., vol. 7, no. 3, 2025, https://doi.org/10.20900/jsr20250059

[101] V. Hristova, K. Haralampiev, I. Vlaev, and S. Karabeliova, “Predicting Pro-Environmental Behavior: The Leading Influence of Environmental Attitudes,” Behav. Sci. (Basel)., vol. 15, no. 3, p. 291, 2025, https://doi.org/10.3390/bs15030291

[102] T. E. Becker, G. Atinc, J. A. Breaugh, K. D. Carlson, J. R. Edwards, and P. E. Spector, “Statistical control in correlational studies: 10 essential recommendations for organizational researchers,” J. Organ. Behav., vol. 37, no. 2, pp. 157–167, 2016, https://doi.org/10.1002/job.2053

[103] J. B. Bernerth and H. Aguinis, “A Critical Review and Best-Practice Recommendations for Control Variable Usage,” Pers. Psychol., vol. 69, no. 1, pp. 229–283, 2016, https://doi.org/10.1111/peps.12103

[104] D. Llanos-Ruiz, V. Abella-García, and V. Ausín-Villaverde, “Virtual Reality in Higher Education: A Systematic Review Aligned with the Sustainable Development Goals,” Societies, vol. 15, no. 9, p. 251, 2025, https://doi.org/10.3390/soc15090251

[105] A. L. Novaes, “Enhancing sustainability education in higher education through simulation-based learning: integrating sustainable development goals,” Int. J. Sustain. High. Educ., vol. 27, no. 5, pp. 1124–1141, 2026, https://doi.org/10.1108/IJSHE-08-2024-0571

[106] D. Irfan, D. Hariyanto, H. Prabowo, Zulhendra, Edidas, and A. Herayono, “Linking Gamification Technology, Motivation, and Flow To Student Engagement and Problem-Solving in Education,” J. Appl. Eng. Technol. Sci., vol. 7, no. 2, pp. 943–959, 2026, https://doi.org/10.37385/a75mdr10

SUPPLEMENTARY

Table S1. Measurement items, study constructs, and corresponding source references.

Construct	Code	Measurement Item	Source Adaptation
Environmental Knowledge	EK1	I understand how daily activities such as energy use, transportation, and consumption contribute to environmental problems.	Frick et al. (2004) [11]
	EK2	I know practical actions that can reduce waste and the use of single-use products.	Frick et al. (2004) [11]
	EK3	I understand which daily actions are relatively more effective in reducing carbon footprint.	Frick et al. (2004) [11]
Environmental Skills	ES1	I am able to compare different product, transportation, or energy-use alternatives based on their environmental impacts.	Olsson et al. (2020) [12]
	ES2	I am able to evaluate environmental information or sustainability claims before making decisions.	Olsson et al. (2020) [12]
	ES3	I am able to develop realistic steps to change my habits toward more sustainable practices.	Olsson et al. (2020) [12]
VR Learning Experience	VRLE1	During the VR experience, I felt present as if I were inside the virtual environment.	Schubert et al. (2001) [25]; Witmer and Singer (1998) [26]
	VRLE2	My attention was focused on the VR experience and was not easily distracted by the real environment.	Schubert et al. (2001) [25]
	VRLE3	The environmental impacts shown in VR felt realistic and relevant to real life.	Schubert et al. (2001) [25]; Makransky and Petersen (2021) [39]
	VRLE4	The interactions in VR helped me understand the relationship between lifestyle choices and ecological consequences.	Makransky and Petersen (2021) [39]
Sustainable Lifestyle	SL1	In the last two weeks, I turned off lights or electrical devices when they were not in use.	Kaiser (1998) [5]; Kaiser and Wilson (2004) [6]
	SL2	In the last two weeks, I reduced the use of single-use items such as plastic bags, disposable bottles, or packaging.	Kaiser (1998) [5]; Lange and Dewitte (2019) [7]
	SL3	In the last two weeks, I chose walking, cycling, ride-sharing, or public transportation whenever possible.	Kaiser and Wilson (2004) [6]; Lange and Dewitte (2019) [7]
	SL4	In the last two weeks, I sorted waste, recycled, repaired, or reused items that were still usable.	Kaiser (1998) [5]; Kaiser and Wilson (2004) [6]
Environmental Attitude	EA1	Humans are severely abusing the environment.	Dunlap et al. (2000) [95]
	EA2	The balance of nature is very delicate and easily upset by human activities.	Dunlap et al. (2000) [95]
	EA3	Unlimited consumption growth may cause serious environmental problems.	Dunlap et al. (2000) [95]

Table S2. Participant Flow Across the Three-Wave Data Collection

Stage	Description	Participants	Exclusion or Loss
Initial recruitment	Students approached through participating faculties or study programs	465	–
Eligibility screening	Students who met inclusion criteria and passed VR safety screening	442	23
Time 1	Completed the pre-VR questionnaire measuring environmental knowledge, environmental skills, environmental attitude, and background variables	430	12
VR session	Completed the standardized VR environmental learning intervention	419	11
Time 2	Completed the post-VR questionnaire measuring VR learning experience and cybersickness symptoms	414	5
Time 3	Completed the two-week follow-up questionnaire measuring sustainable lifestyle	405	9
Data screening	Responses retained after screening for missing data, attention checks, straight-lining, and response-time quality	400	5
Final sample	Valid responses used for CFA and CB-SEM analysis	400	–