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Siri' Na Pacce-based virtual reality STEM projects in science learning: Environmental knowledge, ecological awareness, and environmental care attitudes

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Abstract

This study examines the relationships between *Siri' Na Pacce* (SNP)-based virtual reality (VR) science, technology, engineering, and mathematics (STEM) projects and students' perceived environmental knowledge (EK), ecological awareness (EA), and environmental care attitudes (ECAs) in science learning. The study was motivated by the need for environmental learning innovations that integrate immersive technology, hands-on STEM projects, and culturally meaningful values. A quantitative post-intervention survey design was employed involving 471 undergraduate students who participated in an eleven-week *SNP*-based VR-STEM project focusing on volcanic eruptions as an environmental and disaster-related science topic. Data were collected using a five-point Likert-scale questionnaire and analyzed using partial least squares structural equation modeling. The results indicated significant positive relationships between students' perceptions of the *SNP*-based VR-STEM project and EK, EA, and ECAs. The model explained 30.0% of the variance in EK, 44.9% in EA, and 64.2% in ECAs. EK was significantly associated with EA and ECAs, while EA was also significantly associated with ECAs. Mediation analysis further showed significant indirect relationships through EK, EA, and their sequential pathway. These findings suggest that culturally grounded immersive STEM learning is associated with ECAs through interconnected cognitive, affective, and attitudinal processes. The study contributes to the literature by demonstrating the potential value of integrating VR-STEM learning with *SNP* values of dignity, responsibility, empathy, and solidarity in environmental and disaster-related science learning.

Keywords: ecological awareness, environmental care attitudes, environmental knowledge, *Siri' Na Pacce*, virtual reality STEM

INTRODUCTION

Climate change, environmental degradation, pollution, and biodiversity loss have become urgent global challenges that threaten human well-being and ecosystem sustainability. Intergovernmental Panel on Climate Change (2021) synthesis report indicates that climate change has produced widespread impacts on natural and social systems, making environmental responses not only technical and political, but also educational. In this context, science learning has an important role in helping students understand environmental problems, develop ecological awareness (EA), and cultivate responsible attitudes toward nature. Education for sustainable development also emphasizes the need to prepare learners with the knowledge, values, attitudes, and behaviors required to act responsibly toward the environment, society, and economy (Al Nuaimi & Al Ghamdi, 2022; C. Chen et al., 2022; S. Y. Chen & Liu, 2020).

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Contribution to the literature

- This study introduces *Siri' Na Pacce* (SNP)-based virtual reality (VR) STEM projects as a culturally grounded learning approach for environmental and disaster-related science education.
- This study shows that students' perceptions of *SNP*-based VR-STEM learning on volcanic eruptions are positively associated with perceived environmental knowledge (EK), EA, and environmental care attitudes (ECAs).
- This study highlights how the integration of *SNP* values of dignity, responsibility, empathy, and solidarity provides a culturally grounded framework for interpreting the relationships between immersive STEM learning and students' environmental orientations.

Project-based science, technology, engineering, and mathematics (STEM) education is relevant to environmental science learning because it integrates science, technology, engineering, and mathematics through authentic projects. Through this approach, students are encouraged to investigate real-world problems, design solutions, test ideas, and reflect on learning outcomes (Lee & Lee, 2025; Lin et al., 2021; Sumarni & Kadarwati, 2020). Environmental problems are complex, interdisciplinary, and closely related to everyday life; therefore, STEM projects can support students' problem-solving, creativity, collaboration, and positive learning attitudes (Ardoin & Heimlich, 2021; Pihkala, 2020; Uralovich et al., 2023).

Alongside the development of STEM learning, VR has created new opportunities for making environmental science learning more immersive and meaningful. VR enables students to engage with simulated environments, observe ecological phenomena, and experience learning situations more concretely (Cho & Park, 2023; Makransky & Petersen, 2021; Petersen et al., 2022).

In STEM education, immersive technologies such as VR have been associated with higher engagement, stronger motivation, improved understanding of complex concepts, and richer collaborative learning experiences (Petersen et al., 2022; Serrano-Ausejo & Mårell-Olsson, 2024; Tene et al., 2024). In environmental education, VR is also considered useful because it can create a sense of presence, stimulate empathy, and strengthen learners' connection with environmental issues (Chiang, 2021; Nelson et al., 2020; Spangenberger et al., 2022).

However, technology-based science learning should not only emphasize innovation and immersion. In the Indonesian context, environmental science learning also needs to be culturally meaningful. One relevant local wisdom is *SNP*, Makassar cultural philosophy that reflects dignity, moral responsibility, empathy, solidarity, and concern for others (Pelras, 1996). In environmental learning, *Siri'* can be interpreted as moral responsibility to protect the dignity of the community and environment, while *Pacce* can be understood as empathy toward ecological damage, living beings, and communities affected by environmental problems. Therefore, integrating *SNP* into VR-based STEM projects may strengthen not only students' EK, but also their EA and ECAs.

Previous studies have shown that VR is not merely an engaging visual medium but is also associated with cognitive and affective learning outcomes (Hajj-Hassan & Chaker, 2024; Thoma et al., 2023). When integrated into project-based learning within a STEM framework, VR has been linked with conceptual understanding and reflective learning experiences (Sahabuddin & Makkasau, 2024). Nevertheless, much of the existing research on immersive technologies in STEM and environmental education has focused on learning engagement, academic performance, or general sustainability awareness (Tene et al., 2024). Studies examining how students' perceptions of *SNP*-based VR STEM projects relate to EK, EA, and ECAs remain limited. Research estimating the structural associations among these constructs in a single integrated model is also scarce.

The hypothesized associations involving students' perceptions of VR-based STEM projects are informed by the cognitive affective model of immersive learning. This model proposes that VR affordances, such as presence, agency, representational fidelity, and embodiment, can activate cognitive-affective processes including interest, intrinsic motivation, self-efficacy, and self-regulation (Jiang et al., 2026; Makransky & Petersen, 2021; Zhi & Wu, 2023). In environmental science learning, immersive experiences may make ecological issues that are abstract, psychologically distant, or difficult to observe directly more concrete and personally meaningful for students (Breves & Schramm, 2021; Essokolo & Robinot, 2022). In addition, the theory of planned behavior supports the interpretation of ECAs as an attitudinal orientation that may shape behavioral intention toward environmental responsibility (Ajzen, 1991). These theories motivate the proposed paths but do not make the present post-only design causal.

Based on this rationale, the present study examines structural associations among students' perceptions of *SNP*-based VR-STEM learning, EK, EA, and ECAs. Partial least squares structural equation modeling (PLS-SEM) was used to estimate the proposed direct and indirect paths among the latent constructs. The exogenous construct represents students' evaluations of the learning experience rather than experimentally manipulated exposure. This study therefore contributes evidence about culturally grounded environmental science learning while avoiding causal attribution to the intervention.

LITERATURE REVIEW AND DEVELOPMENT HYPOTHESIS

SNP-Based VR STEM Projects in Science Learning

SNP-based VR STEM projects refer to science learning activities that integrate immersive VR experiences, project-based STEM tasks, and Makassar local wisdom in the context of environmental and disaster-related science learning. In this study, the learning project focused on the topic of volcanic eruption, in which students explored volcanic processes, eruption materials, environmental impacts, and risk-reduction strategies through VR simulation and STEM-based project activities.

Project-based STEM Education supports authentic problem solving by encouraging students to investigate scientific phenomena, apply scientific reasoning, design physical models, analyze environmental impacts, and evaluate project outcomes (AlAli, 2024; F. Chen & Chen, 2025; Vyas & Dalvi, 2023). Within this framework, VR enriches learning by allowing students to observe volcanic phenomena, such as magma movement, lava flow, volcanic ash, gas emissions, and eruption hazards, in a more concrete and immersive way. Such experiences are important because volcanic eruptions are complex natural phenomena that are difficult and dangerous to observe directly in real learning settings (Tene et al., 2024; Urválková & Surynková, 2022). The STEM project component then allows students to transform their virtual observations into hands-on activities, such as constructing a volcanic eruption model, identifying eruption components, explaining cause-and-effect relationships, and discussing environmental consequences for surrounding communities.

The novelty of this study lies in the integration of *SNP* values into VR-based STEM projects. *Siri'* reflects dignity, responsibility, and moral self-awareness, while *Pacce* reflects empathy, solidarity, and concern for others (Pelras, 1996). In the context of volcanic eruption learning, these values help students interpret disasters not only as geological events, but also as environmental and social issues that require responsibility, empathy, preparedness, and care for affected communities. Therefore, *SNP*-based VR STEM projects may support the cognitive, affective, and attitudinal dimensions of environmental science learning by connecting scientific understanding of volcanic eruptions with EA and ECAs.

SNP-Based VR STEM Projects and EK

EK refers to students' understanding of ecosystem structure, ecological processes, environmental problems, human impacts on nature, and sustainable solutions. EK is not limited to factual recall, but also includes analytical reasoning, conceptual integration, and evidence-based interpretation of ecological phenomena (Kazazoglu, 2025; UNESCO, 2024; Xiong et al., 2025; Yang et al., 2023). VR-based STEM projects can strengthen EK by allowing students to observe ecological processes that may be difficult to access in conventional classrooms. Through immersive simulations, students can explore pollution flows, biodiversity loss, ecosystem imbalance, or climate-related environmental changes. Such experiential learning supports constructivist learning because students build knowledge through active experience and inquiry (Urválková & Surynková, 2022). The STEM component further strengthens knowledge construction through scientific investigation, data analysis, engineering design, and mathematical reasoning (Tan et al., 2023; Nugraha et al., 2024). When *SNP* values are integrated, students are encouraged to connect scientific understanding with moral responsibility and local cultural meaning.

H1. Students' perceptions of *SNP*-based VR-STEM learning are positively associated with EK.

SNP-Based VR STEM Projects and EA

EA refers to students' sensitivity to the relationship between humans and natural ecosystems. It includes awareness of ecological vulnerability, empathy toward non-human life, and recognition of the consequences of human actions on the environment (Lambert, 2024; Talgorn & Ullerup, 2023). Unlike EK, EA operates at the intersection of cognition and affect. VR can support EA because immersive simulations can place students in ecologically threatened environments and stimulate emotional responses such as concern, empathy, and urgency (Hazrat et al., 2023; May et al., 2024). In project-based STEM learning, students are also encouraged to conduct inquiry, analyze environmental problems, and design solutions, which can deepen their awareness of human-environment interdependence (Dharin, 2025; Peretz, 2025; Sánchez & Rojas, 2026). The integration of *SNP* strengthens this process because *Pacce* emphasizes empathy and solidarity, while *Siri'* emphasizes responsibility to prevent harmful actions toward others and the environment.

H2. Students' perceptions of *SNP*-based VR-STEM learning are positively associated with EA.

SNP-Based VR STEM Projects and ECAs

ECAs refer to students' concern for environmental quality, commitment to sustainability, and readiness to support actions that reduce ecological harm (Aslam et al., 2021; Li et al., 2020). In environmental literacy, attitudes occupy an important position because they connect cognitive understanding and affective awareness with behavioral intention. VR-based environmental learning can shape ECAs through presence-induced affect, namely emotionally meaningful experiences of environmental threat or beauty that may leave an attitudinal impact (Chuang et al., 2025; X. Chen et al., 2024). In project-based learning integrated with STEM, this attitude formation is strengthened through collaborative work, reflective practice, and the experience of designing solutions for real environmental problems (Koskela & Paloniemi, 2023; Leijen et al., 2020). *SNP* values further support ECAs by framing care for the environment as a cultural and moral responsibility.

H3. Students' perceptions of *SNP*-based VR-STEM learning are positively associated with ECAs.

EK and EA

EK is an important cognitive foundation for EA. Students who understand biodiversity, climate dynamics, ecosystem functions, and the consequences of human activity are more likely to recognize ecological vulnerability and environmental risks (Amprazis & Papadopoulou, 2025; Chander et al., 2025). Systems-oriented EK can strengthen students' holistic ecological perception because they are able to understand feedback loops, thresholds, and cascading effects in ecological systems (Montefusco & Angeli, 2025). In *SNP*-based science learning, EK is not only scientific information, but also a basis for moral reflection. When students understand environmental damage, they may become more aware that ecological problems affect human dignity, social life, and community sustainability.

H4. EK is positively associated with EA.

EK and ECAs

EK is expected to be positively associated with ECAs. Students who understand the causes, consequences, and possible solutions to environmental problems may perceive those problems as serious, personally relevant, and solvable (Emilsson, 2022). Knowledge of sustainable development and circular economy principles may also be associated with a stronger sense of efficacy, an important correlate of pro-environmental attitudes (Adeyemi, 2025). Previous studies have reported positive relationships between EK and attitudes toward ecological responsibility and sustainability (Khazen et al., 2025). Participatory learning studies have likewise reported concurrent changes in ecological knowledge and environmental attitudes (Børresen et al., 2023; Thoma et al., 2023). Accordingly, the present study tests whether higher EK covaries with stronger ECAs.

H5. EK is positively associated with ECAs.

EA and ECAs

EA is closely related to ECAs because awareness includes emotional sensitivity, ecological connectedness, and concern for environmental conditions. Students who feel connected to nature and recognize the consequences of ecological damage are more likely to develop caring attitudes toward the environment (Danatzis et al., 2022). This relationship is also supported by attitude formation theory, which suggests that affectively charged beliefs may be stronger predictors of attitudes than purely cognitive beliefs (Urválková & Surynková, 2022). In environmental care, awareness functions as an affective schema that makes ecological problems personally meaningful and morally significant (Casoli et al., 2025). The value of *Pacce* is particularly relevant here because it emphasizes empathy and concern, which can strengthen students' ECAs.

H6. EA is positively associated with ECAs.

Mediating Role of EK and EA

The proposed relationship between students' perceptions of *SNP*-based VR-STEM learning and ECAs may include indirect associations through EK and EA. Environmental literacy theory connects cognitive, affective, and attitudinal dimensions of environmental learning (Kaldaras et al., 2021; Khatri et al., 2026), while immersive-learning research links subjective ecological connectedness with environmental dispositions (Spangenberger et al., 2022). In the proposed model, *SNP* provides a cultural frame connecting perceived knowledge and EA with responsibility, empathy, and care. Because all constructs were measured at the same post-intervention time point, the indirect paths are statistical mediation patterns rather than evidence of temporal or causal mechanisms.

H7. There is a positive specific indirect association between students' perceptions of *SNP*-based VR-STEM learning and ECAs through EK.

H8. There is a positive specific indirect association between students' perceptions of *SNP*-based VR-STEM learning and ECAs through EA.

H9. There is a positive sequential indirect association between students' perceptions of *SNP*-based VR-STEM learning and ECAs through EK and EA.

MATERIAL AND METHOD

This study used a quantitative post-intervention cross-sectional survey design to examine structural associations among four latent variables: students' perceptions of *SNP*-based VR STEM learning, EK, EA, and ECAs. All participants completed the same eleven-week learning sequence; however, the study did not include a pretest, control group, comparison condition, or experimentally manipulated variation in exposure.

Table 1. Demographic characteristics of participants (n = 471)

Characteristic	Category	n (%)
Gender	Female	298 (63.3)
	Male	173 (36.7)
Age (years)	18–20	214 (45.4)
	21–23	219 (46.5)
	24 or above	38 (8.1)
Faculty	Environmental education	142 (30.1)
	Engineering	118 (25.1)
	Education	96 (20.4)
	Others	115 (24.4)

Accordingly, the exogenous construct represented students' retrospective perceptions of the *SNP*-based VR-STEM learning experience rather than an experimentally assigned intervention. A PLS-SEM approach was used to estimate the direct and indirect associations among these latent constructs. The model's in-sample explanatory performance was assessed using the coefficient of determination (R^2), whereas out-of-sample predictive performance was evaluated separately using Q^2_predict and PLSpredict. Therefore, the estimated structural paths were interpreted as associative and predictive relationships rather than causal effects of the learning intervention.

Participants and Sampling Technique

The participants were undergraduate students at Universitas Negeri Makassar who had completed an eleven-week *SNP*-based VR STEM project in science learning. Purposive sampling was applied because participants needed to have direct experience with the intervention. From 494 initial responses, 23 were excluded due to incomplete data or careless response patterns, resulting in a final sample of 471 students. The inclusion criteria were active student status, completion of the intervention, and willingness to provide informed consent. Students were excluded if they missed more than 20% of the sessions or submitted incomplete questionnaires. No teachers, lecturers, instructors, or facilitators were included as respondents; their involvement was limited to delivering or supporting the learning activities.

Table 1 summarizes the demographic characteristics of the final sample after the application of the inclusion and exclusion criteria.

Measurement Instruments

Data were collected using a 30-item self-report questionnaire rated on a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). The initial item pool was adopted from previously published instruments and subsequently adapted to the Indonesian higher-education context and the *SNP*-based VR learning experience integrated with STEM. The instrument comprised five items measuring EK (PL1-PL5), nine items measuring EA (KE1-KE9), nine items measuring ECAs (KL1-KL9), and seven items measuring students' perceptions of the VR-STEM learning experience (X1-X7). The VR and project-based learning items were adapted from Makransky and Lilleholt (2018) and Al-Abdullatif et al. (2021), with the cultural framing informed by Pelras' (1996) account of *SNP* values. The EK items were adapted from Feigin et al. (2023) and Leal Filho et al. (2021), the EA items from Sternäng and Lundholm (2010) and Stevenson (2014), and the ECA items from Dunlap et al. (2000) and Kaiser et al. (1999).

Before data collection, the adapted questionnaire underwent expert review by three validators. The experts evaluated each item in terms of construct relevance, semantic clarity, linguistic appropriateness, contextual suitability for Indonesian university students, and consistency with the *SNP*-based VR-STEM learning context. This expert-review process was used to strengthen the content and contextual appropriateness of the adapted items. The questionnaire was revised in accordance with their comments and recommendations before being administered in Indonesian. The values associated with *SNP*, including dignity, responsibility, empathy, solidarity, and mutual care, were incorporated through the cultural framing of the learning experience and the contextual interpretation of the VR-STEM construct rather than by explicitly inserting the term *SNP* into every questionnaire item. **Appendix A** presents the complete Indonesian wording, author-prepared English translation, construct assignment, primary adaptation source, and final retention status of all 30 original questionnaire items. Because EK was assessed through students' self-reported knowledge and understanding rather than an objective achievement test, the construct is consistently referred to as EK.

Intervention Procedure

The eleven-week learning sequence was conducted once per week as part of the formal course schedule and integrated an Indonesian-language VR simulation, group-based STEM project activities, discussions, and reflection on *SNP* values. Following orientation and VR familiarization in week 1-week 2, the VR simulation was implemented once per week during Weeks 3-6. During each VR session, each student received approximately 10-15 minutes of individual exposure through a rotational procedure. The simulation, entitled Simulasi: Gunung meletus, was delivered using an oculus VR headset and represented key stages and consequences of volcanic activity, including magma activity, pressure build-up, eruption processes, lava flow, volcanic ash, cooling processes, and associated environmental consequences. Students experienced the VR simulation individually on a rotational basis. While one student used the VR equipment, the other members of the group completed practical learning tasks, recorded observations, and discussed the volcanic phenomena represented in the simulation. Following the VR exploration activities, students worked collaboratively in groups of four to five members to plan, design, construct, test, revise, and present a physical model of a volcanic eruption based on STEM principles. This sequence allowed students to connect observations from the immersive simulation with hands-on project development and discussion of the scientific and environmental implications of volcanic eruptions.

The lecturer, supported by teaching assistants, introduced and reinforced the relevant scientific concepts, guided classroom and group discussions, provided feedback during project development, and assessed the final project products. Teaching assistants were responsible for operating the VR equipment, coordinating student rotations and activity transitions, monitoring the safe use of the equipment, and providing technical assistance when required. Throughout these activities, *SNP* values were incorporated through reflection and collaborative practices emphasizing dignity, responsibility, empathy, solidarity, mutual respect, and concern for communities and environments affected by volcanic disasters. Each group’s final volcanic-eruption model was assessed by the lecturer using a five-point rating rubric. The ratings were applied to the predetermined project-assessment criteria used in the course. Because all project products were assessed by the same course lecturer, no inter-rater reliability procedure was conducted. The sequence of learning objectives, activities, VR implementation, project development, and cultural-value integration across the eleven-week intervention is summarized in **Table 2**.

Table 2. Eleven-week *SNP*-based VR-STEM learning sequence

Week	Learning objective/focus	Main activities	VR exposure	STEM project	SNPI
1	Orientation to the learning sequence and responsible participation in VR-STEM activities	Introduction to the eleven-week learning sequence, explanation of learning procedures, introduction to the VR equipment, safety instructions, and expectations for student participation	VR orientation and familiarization with the headset and controllers	–	[S]
2	Familiarization with VR use and preparation for immersive volcanic-eruption learning	Students practiced using the VR equipment, navigation and interaction procedures, and individual VR rotation procedures	VR familiarization and guided practice	–	[S]
3	Observing initial volcanic processes and identifying major volcanic phenomena	Students individually explored the volcanic-eruption simulation; other group members recorded observations and discussed the phenomena represented	Individual VR exposure, approximately 10-15 min/student; magma activity and pressure build-up	Observation-based preparation for project work	[S] [P]
4	Understanding eruption processes and their environmental consequences	Students continued VR exploration, recorded observations of eruption processes and volcanic materials, and discussed cause-and-effect relationships	Individual VR exposure, approximately 10-15 min/student; eruption processes and lava flow	Connecting VR observations with later model development	[S] [P]
5	Identifying volcanic materials and recognizing their environmental impacts	Students observed volcanic ash, gases, and eruption consequences, documented observations, and discussed environmental implications	Individual VR exposure, approximately 10-15 min/student; ash, gases, and environmental impacts	Group discussion and collection of observations for the volcanic-eruption model	[S] [P]
6	Integrating understanding of volcanic processes, environmental consequences, and disaster awareness	Students completed the VR exploration sequence and consolidated their observations of volcanic processes and environmental consequences	Individual VR exposure, approximately 10-15 min/student; cooling processes and environmental consequences	Consolidation of VR observations as a basis for project planning	[S] [P]
7	Planning the STEM volcanic-eruption project	Students worked in groups of 4-5 to plan and design a physical volcanic-eruption model based on previous observations	-	Planning and designing the volcanic-eruption model	[S] [P]
8	Developing and testing the volcanic-eruption model	Groups constructed and tested their volcanic-eruption models; the lecturer provided guidance and feedback	-	Construction and testing of the volcanic-eruption model	[S] [P]

Table 2 (Continued).

Week	Learning objective/focus	Main activities	VR exposure	STEM project	SNPI
9	Evaluating, revising, and refining the STEM project	Students evaluated model performance, identified aspects requiring improvement, and revised their products based on discussion and feedback	-	Evaluation, revision, and refinement of the model	[S] [P]
10	Presenting and evaluating the final STEM project	Groups presented their volcanic-eruption models, explained scientific and environmental aspects, and received feedback	-	Presentation and evaluation of the final volcanic-eruption model	[S] [P]
11	Reflecting on the learning experience and completing the post-intervention survey	Students reflected on the VR-STEM experience, discussed environmental and community implications, and completed the post-intervention questionnaire	-	Reflection on the STEM project and its environmental implications	[S] [P]

Note. SNPI: *SNP* integration; [S]: *Siri'*; & [P]: *Pacce*

Data Analysis

Data were analyzed using PLS-SEM within the RStudio environment. The analysis comprised two main stages: measurement model assessment and structural model assessment. PLS-SEM was selected because the study aimed to estimate a theoretically specified network of direct and indirect associations among latent constructs while also evaluating the model's explanatory and predictive performance. Prediction was therefore assessed separately through Q^2_predict and PLSpredict rather than inferred solely from the in-sample R^2 values. For the reflective measurement model, indicator reliability was evaluated using outer loadings; internal consistency reliability was assessed using Cronbach's alpha, Dijkstra-Henseler's rho (rho_A), and composite reliability (CR); and convergent validity was examined using average variance extracted (AVE). Discriminant validity was assessed using the Fornell-Larcker criterion and the heterotrait-monotrait (HTMT) ratio. Outer loadings above 0.708, CR values above 0.70, AVE values above 0.50, and HTMT values below 0.90 were used as the principal criteria for evaluating measurement quality (Hair et al., 2017, 2019; Sarstedt et al., 2022).

The structural model was evaluated using inner-model variance inflation factors (VIFs), path coefficients, the R^2, and effect size (f^2). Inner-model VIFs were examined to identify potential collinearity among the predictor constructs, R^2 was used to evaluate the model's explanatory power, and f^2 was used to assess the practical contribution of each predictor. Predictive relevance and out-of-sample predictive performance were assessed using Q^2_predict and PLSpredict. Possible common-method bias was examined through procedural considerations and full-collinearity VIFs as a statistical assessment. Direct, specific indirect, total indirect, and total effects were estimated and reported. Statistical significance was evaluated through bootstrapping with 5,000 resamples using two-tailed tests and two-sided 95% percentile confidence intervals (CIs), which were not bias-corrected. The bootstrap procedure generated standard errors, t-values, p-values, and CIs; a structural coefficient was considered statistically significant when its CI did not include zero and its p-value was below 0.05. Mediation was classified according to the significance and direction of the direct and indirect effects. Complementary partial mediation was identified when the corresponding direct and indirect effects were both statistically significant and had the same direction (Hair et al., 2017, 2019).

RESULTS

Measurement Model Assessment

The original instrument contained 30 indicators, whereas the final model retained 15: X1-X4 for students' perceptions of the *SNP*-based VR-STEM learning experience; PL1-PL5 for EK; KE1-KE3 for EA; and KL5, KL8, and KL9 for ECAs. The full 30-item measurement model was estimated to be using the 471 responses and the same reflective PLS specification. This model showed discriminant-validity concerns, with HTMT values of 0.906 for SNP-VR-STEM-EA and 0.974 for EA-ECA. To document the statistical basis for item exclusion, each deleted indicator was evaluated individually by adding it to the final measurement model. **Appendix B** reports the assigned-construct loading, highest loading on another construct, and maximum HTMT involving the assigned construct for each deleted indicator. These diagnostics supported the exclusion of X5, KE5-KE9, and KL1 because at least one specified measurement criterion was not met. In contrast, X6, X7, KE4, KL2-KL4, KL6, and KL7 met the specified loading, CR, AVE, and HTMT criteria; therefore, the evaluated statistical criteria did not support their exclusion. Because only three of the original nine indicators were retained for both EA and ECAs, the final measurement specifications cover narrower portions of the original construct domains. In particular, the retained environmental-care indicators emphasize VR-linked recognition and sensitivity to

Table 3. Outer loadings

Construct	Indicator	Outer loading	Interpretation
SNP-VR STEM	X1	0.872	Valid
SNP-VR STEM	X2	0.927	Valid
SNP-VR STEM	X3	0.899	Valid
SNP-VR STEM	X4	0.900	Valid
EK	PL1	0.785	Valid
EK	PL2	0.804	Valid
EK	PL3	0.790	Valid
EK	PL4	0.770	Valid
EK	PL5	0.723	Valid
EA	KE1	0.613	Acceptable
EA	KE2	0.894	Valid
EA	KE3	0.921	Valid
ECAs	KL5	0.738	Valid
ECAs	KL8	0.877	Valid
ECAs	KL9	0.897	Valid

Notes. SNP-VR STEM: Students' perceptions of the *SNP*-based VR STEM learning experience & the SNP-VR STEM score is a perception measure, not a manipulated treatment indicator

environmental and social impacts rather than the broader range of environmental attitudes and behavioral willingness represented in the original item pool (**Table 3**).

All retained indicators except KE1 exceeded the recommended outer-loading benchmark of 0.708. KE1 had an outer loading of 0.613 and was retained to preserve content coverage because it captures students' recognition of environmental degradation in their immediate residential surroundings, a facet not represented by KE2 and KE3. Because only three ecological-awareness indicators were retained, removing KE1 would further narrow the content represented by this construct. With KE1 included, EA had CR = 0.858 and AVE = 0.675. In the sensitivity model without KE1, the loadings of KE2 and KE3 increased to 0.947 and 0.955, respectively, with CR = 0.950 and AVE = 0.904. EK→EA changed from β = 0.618 to 0.586 (95% bootstrap CI [0.491, 0.676]), EA→ECA changed from β = 0.299 to 0.280 (95% CI [0.203, 0.356]), and the sequential indirect association SNP-VR-STEM→EK→EA→ECA changed from β = 0.101 to 0.090 (95% CI [0.060, 0.126]). All three CIs remained above zero. In contrast, SNP-VR-STEM→EA changed from β = 0.088 to 0.072 (95% CI [-0.021, 0.157]), and the indirect association SNP-VR-STEM→EA→ECA changed from β = 0.026 to 0.020 (95% CI [-0.006, 0.045]); both CIs included zero when KE1 was omitted. Accordingly, **H2** and **H8** were not supported in the model without KE1, whereas **H4**, **H6**, and **H9** remained supported. KE1 was therefore retained to preserve content coverage, while the findings for **H2** and **H8** are interpreted cautiously. The sensitivity model used 5,000 bootstrap resamples and two-sided percentile 95% CIs.

Table 5. Fornell-Larcker criterion

Construct	SNP-VR STEM	EK	EA	ECA
SNP-VR STEM	0.900			
EK	0.548	0.775		
EA	0.427	0.666	0.821	
ECA	0.728	0.608	0.605	0.840

Table 6. HTMT values

Relationship	HTMT
EK-SNP-VR STEM	0.627
EA-NP-VR STEM	0.518
ECA-SNP-VR STEM	0.847
EA-EK	0.841
ECA-EK	0.758
ECA-EA	0.799

All constructs had Cronbach's alpha, rhoA, and CR values above 0.70. The AVE values were also above 0.50. These results indicate that all constructs met the requirements for internal consistency reliability and convergent validity (**Table 4**).

The Fornell-Larcker results show that the square root of AVE for each construct was higher than its correlations with other constructs. This indicates that the constructs had acceptable discriminant validity based on the Fornell-Larcker criterion (**Table 5**).

The HTMT values were all below 0.90, indicating that the final model met the discriminant validity criterion. This means that *SNP*-based VR STEM learning, EK, EA, and ECAs can be interpreted as distinct constructs (**Table 6**).

Structural Model Assessment

The structural model was assessed using inner-model VIFs, structural path coefficients, R^2, f^2, and bootstrapping (**Table 7**). The paths represent conditional associations among latent-variable scores. They do not estimate intervention effects because the study did not manipulate exposure, collect a pretest, or include a comparison group. Predictive relevance and relative out-of-sample performance were additionally evaluated using Q^2_predict and PLSpredict benchmark comparisons.

As shown in **Table 7**, the inner-model VIF values ranged from 1.000 to 2.121, with the highest value

Table 4. Construct reliability and convergent validity

Construct	Cronbach's alpha	rhoA	CR	AVE	Interpretation
SNP-VR STEM	0.921	0.921	0.944	0.809	Reliable and valid
EK	0.833	0.836	0.882	0.600	Reliable and valid
EA	0.743	0.791	0.858	0.675	Reliable and valid
ECAs	0.787	0.797	0.877	0.706	Reliable and valid

Table 7. Inner-model VIFs

Endogenous construct	Predictor	Inner VIF	Interpretation
EK	Perceived SNP-VR STEM experience	1.000	No structural collinearity concern
EA	Perceived SNP-VR STEM experience	1.429	No structural collinearity concern
EA	EK	1.429	No structural collinearity concern
ECAs	Perceived SNP-VR STEM experience	1.443	No structural collinearity concern
ECAs	EK	2.121	No structural collinearity concern
ECAs	EA	1.815	No structural collinearity concern

Table 8. R^2

EC	R^2	Adjusted R^2	Interpretation
EK	0.300	0.299	Moderate explanatory power
EA	0.449	0.447	Moderate explanatory power
ECAs	0.642	0.640	Substantial explanatory power

Note. EC: Endogenous construct

Table 9. Q^2_predict and PLSpredict results

Construct	Indicator	Q^2_predict	PLS RMSE	LM RMSE
EK	PL1	0.1716	0.6593	0.6521
EK	PL2	0.1550	0.6920	0.6915
EK	PL3	0.1617	0.6700	0.6710
EK	PL4	0.1972	0.6597	0.6560
EK	PL5	0.1929	0.6519	0.6539
EA	KE1	0.1909	0.7612	0.7781
EA	KE2	0.3228	0.6631	0.6505
EA	KE3	0.3746	0.6588	0.6502
ECA	KL5	0.3734	0.6394	0.5838
ECA	KL8	0.4614	0.5529	0.5413
ECA	KL9	0.5045	0.5451	0.5408

Note. PLS: Partial least squares; LM: Linear model; RMSE: Root mean square error; & Q^2_predict: Out-of-sample predictive relevance statistic

observed for EK as a predictor of ECAs. All values were below the conservative threshold of 3.3, indicating that structural collinearity was not a concern and that the path coefficients could be interpreted without substantial collinearity-related distortion.

The model accounted for 30.0% of the in-sample variance in EK, 44.9% in EA, and 64.2% in ECAs. These R^2 values describe explanatory performance within this sample and should not be interpreted as evidence of causal impact or out-of-sample predictive accuracy (**Table 8**).

As shown in **Table 9**, all Q^2_predict values were positive, ranging from 0.1550 to 0.5045, indicating that the model had predictive relevance for all endogenous indicators. The PLS-SEM model produced lower RMSE values than the linear-model benchmark for three indicators (PL3, PL5, and KE1), whereas the linear model

Table 11. f^2

Path	f^2	Interpretation
SNP-VR STEM → EK	0.429	Large effect
SNP-VR STEM → EA	0.010	Very small effect
SNP-VR STEM → ECA	0.431	Large effect
EK → EA	0.484	Large effect
EK → ECA	0.018	Small effect
EA → ECA	0.133	Small to medium effe

produced lower values for the remaining indicators. Overall, the positive Q^2_predict values supported the model's predictive relevance, although its out-of-sample predictive performance was modest and varied across indicators relative to the linear-model benchmark.

All six reported structural coefficients were positive and met the manuscript's stated significance criterion. The associations between perceived SNP-VR STEM experience and EK (β = 0.548) and ECAs (β = 0.538) were comparatively large. In contrast, the association with EA was small (β = 0.088) and had a very small practical contribution (f^2 = 0.010), despite being statistically significant. EK was positively associated with EA (β = 0.618) and ECAs (β = 0.114), while EA was positively associated with ECAs (β = 0.299). These coefficients describe relationships among students' self-reported perceptions and outcomes, not effects produced by the intervention (**Table 10**).

The effect-size results showed that the largest practical contributions were observed for the paths from EK to EA, perceived SNP-VR-STEM experience to ECAs, and perceived SNP-VR-STEM experience to EK (**Table 11**).

The association between perceived SNP-VR-STEM experience and EA was statistically significant but had a very small practical contribution (f^2 = 0.010). This pattern indicates that EA was more strongly associated with EK than with students' perceptions of the SNP-VR-STEM learning experience.

Table 10. Direct structural path coefficients

Hypothesis	Path	β	t-value	95% CI	p-value	Decision
H1	SNP-VR STEM → EK	0.548	11.230	[0.446, 0.636]	< 0.001	Supported
H2	SNP-VR STEM → EA	0.088	1.979	[0.004, 0.177]	0.041	Supported
H3	SNP-VR STEM → ECA	0.538	11.713	[0.441, 0.625]	< 0.001	Supported
H4	EK → EA	0.618	13.375	[0.523, 0.703]	< 0.001	Supported
H5	EK → ECA	0.114	2.497	[0.029, 0.208]	0.011	Supported
H6	EA → ECA	0.299	7.018	[0.214, 0.384]	< 0.001	Supported

Table 12. Specific indirect effects

Hypothesis	Indirect path	OE	BM	BSD	t-value	95% CI	p-value	Decision
H7	SNP-VR STEM → EK → ECA	0.063	0.064	0.027	2.334	[0.014, 0.119]	0.011	Supported
H8	SNP-VR STEM → EA → ECA	0.026	0.026	0.014	1.872	[0.001, 0.057]	0.041	Supported
H9	SNP-VR STEM → EK → EA → ECA	0.101	0.102	0.019	5.460	[0.067, 0.141]	< 0.001	Supported

Note. OE: Original estimate; BM: Bootstrap mean; BSD: Bootstrap standard deviation;

Table 13. Direct, indirect, and total structural associations

Relationship	Direct	Total indirect	Total	Total 95% CI	Total p	Interpretation
Perceived SNP-VR STEM → EK	0.548	-	0.548	[0.446, 0.636]	< 0.001	Direct association only
Perceived SNP-VR STEM → EA	0.088	0.338	0.427	[0.340, 0.510]	< 0.001	Indirect component through EK
Perceived SNP-VR STEM → ECAs	0.538	0.190	0.728	[0.668, 0.780]	< 0.001	Complementary partial mediation
EK → EA	0.618	-	0.618	[0.523, 0.703]	< 0.001	Direct association only
EK → ECAs	0.114	0.185	0.299	[0.220, 0.387]	< 0.001	Indirect component through EA
EA → ECAs	0.299	-	0.299	[0.214, 0.384]	< 0.001	Direct association only

Mediation Analysis

Specific indirect associations were estimated using 5,000 bootstrap resamples. An indirect coefficient was treated as statistically supported when its reported CI excluded zero and its p-value was below 0.05. The terms indirect association and statistical mediation are used descriptively; the post-intervention cross-sectional design cannot establish temporal ordering or a causal mechanism (**Table 12**).

As shown in **Table 12**, all three specific indirect effects had reported p-values below 0.05 and 95% CIs that did not include zero. The indirect association between perceived SNP-VR-STEM experience and ECAs through EK was statistically significant ($\beta = 0.063$, $p = 0.011$, 95% CI [0.014, 0.119]), supporting **H7**. The indirect pathway through EA was also supported, although its magnitude was comparatively small and close to the significance threshold ($\beta = 0.026$, $p = 0.041$, 95% CI [0.001, 0.057]), supporting **H8**. The sequential pathway through EK and EA was the strongest specific indirect association ($\beta = 0.101$, $p < 0.001$, 95% CI [0.067, 0.141]), supporting **H9**. These findings show statistically supported indirect associations among self-reported constructs and should not be interpreted as evidence of causal mediation.

As shown in **Table 13**, all total structural associations were positive and statistically significant, with their 95% CIs excluding zero. The largest total association was observed between perceived SNP-VR-STEM experience and ECAs ($\beta\_total = 0.728$), comprising a direct component of 0.538 and a total indirect component of 0.190, indicating complementary partial mediation. Perceived SNP-VR-STEM experience was also associated with EA both directly ($\beta = 0.088$) and indirectly through EK ($\beta\_indirect = 0.338$), resulting in a total association of 0.427. Furthermore, the total association between EK and ECAs was 0.299, comprising a direct component of 0.114 and an indirect component of 0.185 through EA. The remaining relationships involved direct associations only. Overall, the findings indicate that EK and EA functioned as complementary pathways within the proposed structural model. However, these mediated relationships represent statistical associations among self-reported constructs rather than causal mechanisms produced by the intervention.

Figure 1 shows the estimated PLS-SEM structural associations. The label SNP_VR_STEM denotes students' perceptions of the *SNP*-based VR-STEM learning experience, not an experimentally assigned intervention. Positive paths connect the perceived experience with EK, EA, and ECAs; perceived knowledge and awareness also show positive paths to ECAs. Indirect paths are consistent with complementary partial mediation, but their cross-sectional ordering should not be interpreted as temporal or causal.

Figure 2 documents the implementation context: one image shows a student using the head-mounted display and hand controller, and the second shows the Indonesian-language volcanic-eruption simulation interface. The interface combines staged volcanic processes, real-time information, identification tasks, learning goals, and *SNP* values. **Figure 2** confirms that immersive content, STEM activities, and cultural prompts were present; it does not by itself demonstrate learning effects.

Figure 3 shows a group volcanic-eruption model produced during the learning sequence. The activity was designed to connect virtual observation with hands-on modeling, scientific explanation, environmental responsibility, disaster preparedness, and care for affected communities. The image documents the product but does not establish that the activity caused changes in the outcomes measured.

DISCUSSION

The findings present a coherent pattern of positive relationships among students' perceptions of *SNP*-based VR-STEM learning, EK, EA, and ECAs. The model explained 64.2% of the in-sample variance in ECAs, demonstrating meaningful explanatory capacity within the proposed structural framework.

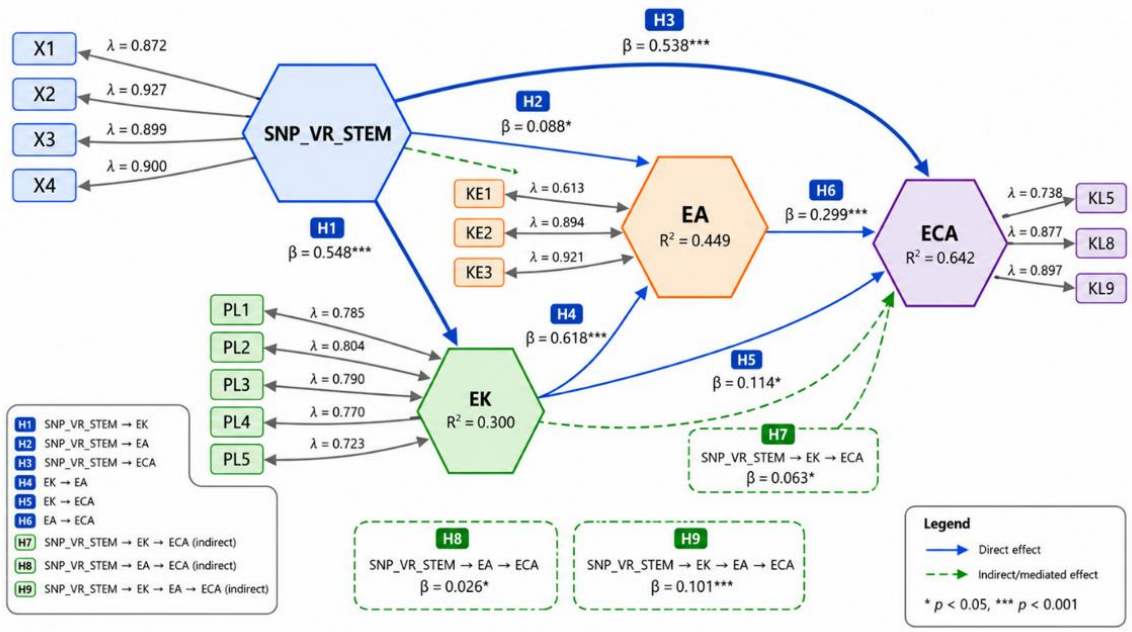

Figure 1. Structural model (created by the authors)

Figure 2. Implementation of SNP-based VR STEM learning and VR environmental simulation interface (photograph taken by the authors during the classroom intervention)

Figure 3. STEM project product for environmental science learning (photograph taken by the authors during the classroom intervention)

During the eleven-week learning sequence, students observed volcanic processes through VR, connected their observations with hands-on STEM projects, and reflected on environmental and community consequences through locally grounded cultural values.

By examining these elements within one integrated model, this study extends previous research on immersive learning, project-based STEM education, and culturally contextualized environmental learning. The overall pattern is consistent with studies linking immersive learning with engagement and conceptual understanding (Makransky & Petersen, 2021; Petersen et al., 2022; Tene et al., 2024).

A comparatively large positive association was found between students' perceptions of the VR-STEM learning experience and EK (β = 0.548, f^2 = 0.429).

Students who evaluated the immersive and project-based learning experience more positively also tended to report greater understanding of environmental phenomena and their consequences. The combination of virtual observation and physical modeling may have helped make volcanic processes and their environmental implications more concrete and meaningful. This interpretation aligns with research associating immersive learning with the understanding of complex scientific concepts (Kuhail et al., 2022; Tene et al., 2024), and project-based STEM learning with interdisciplinary problem solving (Lee & Lee, 2025; Lin et al., 2021; Sumarni & Kadarwati, 2020). The result highlights EK as an important component of students' evaluations of the integrated learning experience.

The direct association between students' perceptions of the VR-STEM experience and EA was positive and statistically supported, although its practical contribution was very small ($\beta = 0.088$, $f^2 = 0.010$). This finding provides a more differentiated understanding of how EA was related to the other constructs. In particular, the total association between perceived VR-STEM experience and EA was considerably larger (β_total = 0.427) because of the indirect component through EK (β_indirect = 0.338). Thus, the model suggests that EK represented a more prominent structural pathway connecting students' evaluations of the learning experience with EA. The volcanic-eruption context provided opportunities for students to consider the consequences of natural processes for land, air, water, living organisms, and surrounding communities. This pattern complements research connecting VR with presence, emotional engagement, and attention to environmental issues (Chiang, 2021; Nelson et al., 2020; Spangenberger et al., 2022).

A comparatively large positive association was also observed between students' perceptions of the VR-STEM experience and ECAs ($\beta = 0.538$, $f^2 = 0.431$). Students who evaluated the learning experience more positively also tended to express stronger environmental concern and responsibility. When the indirect pathways were included, the total association reached 0.728, consisting of a direct component of 0.538 and a total indirect component of 0.190. This result indicates that the relationship involved both a substantial direct association and complementary pathways through EK and EA. The pattern is consistent with research associating emotionally meaningful VR experiences with pro-environmental attitudes (Plechatá et al., 2024; Putra et al., 2026) and collaborative project activities with agency and reflection (Koskela & Paloniemi, 2023; Leijen et al., 2020). Within the pedagogical context, *SNP* values provided a culturally relevant framework for connecting scientific learning with dignity, empathy, solidarity, responsibility, and environmental care.

EK had a comparatively large positive association with EA ($\beta = 0.618$, $f^2 = 0.484$), emphasizing the close relationship between students' perceived understanding of environmental issues and their sensitivity to ecological conditions. Its direct association with ECAs was smaller ($\beta = 0.114$, $f^2 = 0.018$), but the total association increased to 0.299 when the indirect pathway through EA (β_indirect = 0.185) was included. This pattern suggests that EA complemented EK in its relationship with ECAs. The result is consistent with studies suggesting that EK is particularly meaningful when it is connected with contextual understanding, reflection, and awareness of ecological consequences (Børresen et al., 2023; Khazen et al., 2025).

EA was positively associated with ECAs ($\beta = 0.299$, $f^2 = 0.133$), indicating a meaningful practical contribution within the structural model. Students who reported greater awareness of ecological vulnerability also tended to express stronger care for the environment. This relationship is consistent with theoretical accounts positioning EA as an affective and moral foundation for pro-environmental attitudes (Casoli & Cappiello, 2025; Danatzis et al., 2022). The values embedded in *SNP* offer a culturally relevant perspective for understanding this relationship through empathy, mutual responsibility, and concern for the well-being of communities and the environment.

The statistical mediation analysis further supported the integrated structure of the proposed model. For the relationship between perceived SNP-VR-STEM experience and ECAs, the direct and indirect associations were statistically significant and operated in the same positive direction, a pattern consistent with complementary partial mediation. Because all constructs were measured at the same post-intervention time point, this classification describes the pattern of structural associations and should not be interpreted as evidence of a temporal or causal mediation mechanism. The strongest specific indirect association between perceived VR-STEM experience and ECAs occurred sequentially through EK and EA ($\beta = 0.101$). The indirect association through EK alone was 0.063, while the association through EA alone was 0.026. Although the latter pathway was comparatively small, it contributed to the overall pattern and helped clarify the relative importance of the proposed pathways. Collectively, the findings suggest that EK and EA serve as complementary structural pathways connecting students' evaluations of the learning experience with ECAs. This pattern is compatible with a cognitive-affective account in which knowledge-related and awareness-related processes jointly correspond with environmental orientations.

The predictive assessment provided additional support while also identifying opportunities for model refinement. All item-level Q^2_predict values were positive, indicating predictive relevance for the endogenous indicators relative to the naïve benchmark. The comparison with the linear-model benchmark showed that predictive performance varied across indicators, with the PLS-SEM model producing lower prediction errors for three of the eleven indicators. These findings indicate that the model possesses predictive relevance, while its out-of-sample performance is modest and indicator-dependent. This result is useful for guiding future model development, particularly by identifying environmental-care-attitude indicators whose prediction may benefit from additional explanatory constructs.

Theoretically, the study contributes an integrated account of how students' perceptions of immersive STEM learning correspond with EK, EA, and ECAs within a culturally grounded pedagogical setting. Practically, the findings suggest the value of connecting VR-based observation with hands-on modeling and structured reflection on dignity, responsibility, empathy, solidarity, disaster preparedness, and environmental care. The prominent associations involving EK and ECAs, together with the complementary indirect pathways, provide a promising foundation for the continued development of *SNP*-based VR-STEM learning. Because the study employed a post-intervention survey without a pretest or comparison group, the structural coefficients are interpreted as associative and predictive relationships rather than causal effects. Future research can build on these promising findings by incorporating longitudinal or experimental designs, objective measures of EK, systematic monitoring of implementation fidelity, and assessments of environmental behavior over time. Overall, the results provide encouraging evidence for the relevance of culturally grounded VR-STEM learning and support its further investigation in environmental science education.

CONCLUSION, LIMITATIONS, AND FUTURE RESEARCH

This study identified a coherent pattern of positive structural associations among students' perceptions of *SNP*-based VR STEM learning, EK, EA, and ECAs. Students who evaluated the VR-STEM learning experience more positively also tended to report higher levels of all three environmental learning constructs. The comparatively large associations with EK ($\beta = 0.548$) and ECAs ($\beta = 0.538$) demonstrate the educational relevance of combining immersive observation, hands-on STEM projects, volcanic-eruption learning, and culturally grounded reflection. Although the direct association with EA was practically very small ($\beta = 0.088$, $f^2 = 0.010$), its total association increased to 0.427 through EK. The model also explained 64.2% of the in-sample variance in ECAs, indicating meaningful explanatory capacity within the proposed structural framework. EK was strongly associated with EA and was also indirectly associated with ECAs through EA. EA, in turn, was positively associated with ECAs. The direct and same-sign indirect relationships were consistent with complementary partial mediation. In particular, the sequential pathway through EK and EA represented the strongest specific indirect association between perceived VR-STEM experience and ECAs. These findings support an integrated cognitive-affective interpretation in which perceived knowledge and EA operate as complementary structural pathways within the model. Accordingly, the study contributes to environmental science education by demonstrating the potential relevance of connecting immersive STEM learning with locally grounded values of dignity, responsibility, empathy, solidarity, and environmental care.

Several limitations should be considered when interpreting these findings. First, the study employed a post-intervention survey without a pretest, control group, or comparison condition. Consequently, the structural coefficients represent associations among students' self-reported constructs rather than causal effects or measured changes produced by the intervention. The cross-sectional data also cannot establish the temporal order assumed in the sequential mediation model. Second, the participants were undergraduate students from one university in Makassar, which may limit the applicability of the findings to other educational levels, regions, institutions, and cultural contexts. Third, all constructs were measured through a questionnaire administered to the same respondents at one point in time. Although common-method bias was statistically assessed, the possibility of shared-method influences cannot be completely excluded. EK was also measured as perceived knowledge rather than through an objective achievement test. Fourth, the final measurement model retained reduced indicator sets for EA and ECAs. Although the retained indicators demonstrated acceptable measurement properties, reducing the original scales may have narrowed the conceptual coverage of these constructs. In addition, the *SNP* dimension was embedded in the pedagogical context rather than explicitly measured through a separate cultural-values scale. The present findings therefore reflect students' evaluations of the complete learning experience and cannot isolate the individual contribution of VR, STEM projects, volcanic-eruption content, or *SNP* values. Finally, the positive Q^2_predict values supported the model's predictive relevance, while comparison with the linear-model benchmark indicated modest and indicator-dependent out-of-sample performance. Further external validation would consequently strengthen the model's predictive application.

Future studies should employ experimental or quasi-experimental designs incorporating pretest and post-test measurements, control or comparison groups, and longitudinal data. Such designs would enable stronger evaluation of learning changes, temporal ordering, and the proposed mediation pathways. Research should also involve broader samples across educational levels, institutions, regions, and cultural settings. Combining self-report questionnaires with objective knowledge tests, interviews, classroom observations, project assessments, and behavioral measures would provide a more comprehensive evaluation of environmental learning outcomes. Further instrument development should examine the conceptual coverage of EA and ECAs, validate the deleted and retained indicators in independent samples, and develop explicit measures of how students perceive the integration of *SNP* values. Future intervention studies should also document implementation fidelity, instructor practices, VR exposure, group participation, and project-assessment procedures more systematically. Comparisons between *SNP* and other local wisdom traditions, as well as applications to different environmental and disaster-related science topics, would help determine how culturally responsive VR-STEM learning can be adapted across diverse educational contexts. Overall, the present findings provide an encouraging foundation for further investigation of culturally grounded immersive STEM learning as an approach to environmental science education.

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APPENDIX A

Table A1. SNP-based VR-STEM context and complete item wording

Construct	Code	Indonesian wording	English translation	Source/adaptation basis	SNP integration	Final status
Perceived *Siri' Na Pacce*-based VR-STEM experience	X1	*Pengalaman VR membuat saya merenungkan dampak erupsi gunung api terhadap lingkungan dan kehidupan masyarakat di sekitarnya.*	The VR experience made me reflect on the impacts of volcanic eruptions on the environment and the lives of surrounding communities.	Makransky & Lilleholt (2018); Al-Abdullatif et al. (2021); cultural framing informed by Pelras (1996)	[P] *Pacce* – empathy and concern for affected communities and environments	Retained
Perceived *Siri' Na Pacce*-based VR-STEM experience	X2	*Saya menyadari bahwa teknologi VR dapat digunakan untuk meningkatkan kepedulian terhadap dampak lingkungan dan risiko bencana gunung api.*	I realize that VR technology can be used to foster concern about the environmental impacts and disaster risks of volcanic eruptions.	Makransky & Lilleholt (2018); Al-Abdullatif et al. (2021); cultural framing informed by Pelras (1996)	[P] *Pacce* – environmental concern and sensitivity	Retained
Perceived *Siri' Na Pacce*-based VR-STEM experience	X3	*Pengalaman dalam VR membuat saya lebih termotivasi untuk mempelajari dan mendukung upaya mengurangi dampak lingkungan akibat erupsi gunung api.*	The VR experience made me more motivated to learn about and support efforts to reduce the environmental impacts of volcanic eruptions.	Makransky & Lilleholt (2018); Al-Abdullatif et al. (2021); cultural framing informed by Pelras (1996)	[S] *Siri'* – moral responsibility and commitment	Retained
Perceived *Siri' Na Pacce*-based VR-STEM experience	X4	*Saya bersedia mendukung penggunaan VR dalam pembelajaran STEM untuk mempelajari erupsi gunung api, lingkungan, dan mitigasi bencana.*	I am willing to support the use of VR in STEM learning to study volcanic eruptions, environmental impacts, and disaster mitigation.	Makransky & Lilleholt (2018); Al-Abdullatif et al. (2021); cultural framing informed by Pelras (1996)	[S] *Siri'* – responsibility and responsible action	Retained
Perceived *Siri' Na Pacce*-based VR-STEM experience	X5	*Setelah mengikuti pembelajaran VR-STEM, saya ingin mengajak orang lain lebih peduli terhadap lingkungan dan masyarakat yang terdampak bencana gunung api.*	After participating in VR-STEM learning, I want to encourage others to care more about the environment and communities affected by volcanic disasters.	Makransky & Lilleholt (2018); Al-Abdullatif et al. (2021); cultural framing informed by Pelras (1996)	[P] *Pacce* – empathy, care, and solidarity	Deleted
Perceived *Siri' Na Pacce*-based VR-STEM experience	X6	*Saya tertarik mengembangkan proyek atau ide kreatif berbasis STEM yang berkaitan dengan erupsi gunung api, lingkungan, dan mitigasi bencana.*	I am interested in developing STEM-based projects or creative ideas related to volcanic eruptions, the environment, and disaster mitigation.	Makransky & Lilleholt (2018); Al-Abdullatif et al. (2021); cultural framing informed by Pelras (1996)	[S] *Siri'* – responsibility and constructive contribution	Deleted
Perceived *Siri' Na Pacce*-based VR-STEM experience	X7	*Pembelajaran VR-STEM mendorong saya untuk bertindak lebih bertanggung jawab terhadap lingkungan dan masyarakat yang berisiko terdampak bencana gunung api.*	VR-STEM learning encourages me to act more responsibly toward the environment and communities at risk of volcanic disasters.	Makransky & Lilleholt (2018); Al-Abdullatif et al. (2021); cultural framing informed by Pelras (1996)	[S+P] *Siri' Na Pacce* – responsibility, empathy, and concern	Deleted
Perceived environmental knowledge	PL1	*Saya memahami bahwa erupsi gunung api dapat menyebabkan perubahan pada kondisi lingkungan dan ekosistem di wilayah sekitarnya.*	I understand that volcanic eruptions can cause changes in environmental conditions and ecosystems in surrounding areas.	Feigin et al. (2023); Leal Filho et al. (2021); contextualized to volcanic-eruption and environmental/disaster learning	Scientific/cognitive content	Retained
Perceived environmental knowledge	PL2	*Saya memahami bagaimana aktivitas magma dan tekanan di dalam gunung api dapat menyebabkan terjadinya erupsi.*	I understand how magma activity and pressure within a volcano can lead to an eruption.	Feigin et al. (2023); Leal Filho et al. (2021); contextualized to volcanic-eruption and environmental/disaster learning	Scientific/cognitive content	Retained
Perceived environmental knowledge	PL3	*Saya mengetahui dampak lava, abu vulkanik, dan material erupsi lainnya terhadap tanah, air, udara, tumbuhan, hewan, dan kehidupan manusia.*	I know the impacts of lava, volcanic ash, and other eruption materials on soil, water, air, plants, animals, and human life.	Feigin et al. (2023); Leal Filho et al. (2021); contextualized to volcanic-eruption and environmental/disaster learning	[P] *Pacce* – concern for living beings, people, and environmental impacts	Retained
Perceived environmental knowledge	PL4	*Saya memahami bahwa erupsi gunung api dapat menimbulkan risiko lingkungan dan bencana bagi masyarakat yang tinggal di wilayah sekitarnya.*	I understand that volcanic eruptions can create environmental and disaster risks for communities living in surrounding areas.	Feigin et al. (2023); Leal Filho et al. (2021); contextualized to volcanic-eruption and environmental/disaster learning	[P] *Pacce* – awareness and concern for affected communities	Retained
Perceived environmental knowledge	PL5	*Saya mengetahui langkah-langkah mitigasi yang dapat dilakukan untuk mengurangi risiko dan dampak lingkungan akibat erupsi gunung api.*	I know mitigation measures that can be taken to reduce the risks and environmental impacts of volcanic eruptions.	Feigin et al. (2023); Leal Filho et al. (2021); contextualized to volcanic-eruption and environmental/disaster learning	[S] *Siri'* – preparedness and responsibility for harm reduction	Retained
Ecological awareness	KE1	*Saya menyadari bahwa erupsi gunung api dapat menyebabkan kerusakan pada lingkungan dan ekosistem di wilayah terdampak.*	I am aware that volcanic eruptions can cause damage to the environment and ecosystems in affected areas.	Sternäng & Lundholm (2010); Stevenson (2014); contextualized to volcanic-eruption ecological awareness	[P] *Pacce* – ecological sensitivity and concern	Retained
Ecological awareness	KE2	*Saya menyadari bahwa lava, abu vulkanik, gas, dan material erupsi lainnya dapat memengaruhi keseimbangan lingkungan dan kehidupan makhluk hidup.*	I am aware that lava, volcanic ash, gases, and other eruption materials can affect environmental balance and living organisms.	Sternäng & Lundholm (2010); Stevenson (2014); contextualized to volcanic-eruption ecological awareness	[P] *Pacce* – sensitivity toward living beings and ecosystems	Retained
Ecological awareness	KE3	*Saya menyadari pentingnya menjaga dan memulihkan lingkungan setelah bencana gunung api untuk keberlanjutan kehidupan masyarakat dan generasi mendatang.*	I am aware of the importance of protecting and restoring the environment after volcanic disasters for the sustainability of communities and future generations.	Sternäng & Lundholm (2010); Stevenson (2014); contextualized to volcanic-eruption ecological awareness	[S+P] *Siri' Na Pacce* – responsibility, empathy, and intergenerational concern	Retained

Table A1 (Continued).

Construct	Code	Indonesian wording	English translation	Source/adaptation basis	SNP integration	Final status
Ecological awareness	KE5	*Saya merasa memiliki tanggung jawab untuk ikut menjaga lingkungan dan membantu mengurangi dampak ekologis yang ditimbulkan oleh bencana gunung api.*	I feel responsible for helping to protect the environment and reduce the ecological impacts caused by volcanic disasters.	Sternäng & Lundholm (2010); Stevenson (2014); contextualized to volcanic-eruption ecological awareness	[S] *Siri'* – personal and moral responsibility	Deleted
Ecological awareness	KE6	*Saya menyadari perlunya menghindari tindakan yang dapat memperburuk kerusakan lingkungan selama proses penanganan dan pemulihan setelah bencana gunung api.*	I am aware of the need to avoid actions that may worsen environmental damage during response and recovery after volcanic disasters.	Sternäng & Lundholm (2010); Stevenson (2014); contextualized to volcanic-eruption ecological awareness	[S] *Siri'* – self-restraint and responsible action	Deleted
Ecological awareness	KE7	*Saya bersedia berpartisipasi dalam kegiatan lingkungan atau mitigasi yang bertujuan membantu masyarakat dan lingkungan di wilayah rawan bencana gunung api.*	I am willing to participate in environmental or mitigation activities aimed at supporting communities and environments in volcanic hazard areas.	Sternäng & Lundholm (2010); Stevenson (2014); contextualized to volcanic-eruption ecological awareness	[S+P] *Siri' Na Pacce* – responsibility, solidarity, and mutual care	Deleted
Ecological awareness	KE8	*Saya percaya bahwa pendidikan tentang gunung api, lingkungan, dan mitigasi bencana penting untuk membangun perilaku yang bertanggung jawab terhadap lingkungan.*	I believe that education about volcanoes, the environment, and disaster mitigation is important for developing environmentally responsible behavior.	Sternäng & Lundholm (2010); Stevenson (2014); contextualized to volcanic-eruption ecological awareness	[S] *Siri'* – moral responsibility	Deleted
Ecological awareness	KE9	*Saya menyadari pentingnya mematuhi aturan keselamatan dan perlindungan lingkungan di wilayah yang memiliki risiko erupsi gunung api.*	I am aware of the importance of complying with safety and environmental protection regulations in areas exposed to volcanic eruption risks.	Sternäng & Lundholm (2010); Stevenson (2014); contextualized to volcanic-eruption ecological awareness	[S] *Siri'* – responsibility and respect for protective norms	Deleted
Environmental care attitudes	KL1	*Saya bersedia ikut menjaga dan memulihkan kondisi lingkungan yang terdampak oleh bencana gunung api meskipun membutuhkan usaha lebih.*	I am willing to contribute to protecting and restoring environments affected by volcanic disasters even when it requires additional effort.	Dunlap et al. (2000); Kaiser et al. (1999); contextualized to VR-based volcanic-eruption learning and the study context	[S] *Siri'* – commitment and environmental responsibility	Deleted
Environmental care attitudes	KL2	*Simulasi VR mendorong saya untuk lebih peduli terhadap kerusakan ekosistem yang dapat terjadi akibat erupsi gunung api.*	The VR simulation encourages me to care more about ecosystem damage that may result from volcanic eruptions.	Dunlap et al. (2000); Kaiser et al. (1999); contextualized to VR-based volcanic-eruption learning and the study context	[P] *Pacce* – ecological concern	Deleted
Environmental care attitudes	KL3	*Pengalaman menggunakan VR membuat saya lebih peduli terhadap dampak erupsi gunung api terhadap manusia, makhluk hidup, dan lingkungan.*	The VR experience makes me more concerned about the impacts of volcanic eruptions on people, living organisms, and the environment.	Dunlap et al. (2000); Kaiser et al. (1999); contextualized to VR-based volcanic-eruption learning and the study context	[P] *Pacce* – empathy and concern for people, living beings, and nature	Deleted
Environmental care attitudes	KL4	*Setelah melihat proses erupsi melalui VR, saya merasa perlindungan lingkungan di wilayah rawan gunung api merupakan hal yang penting.*	After observing the eruption process through VR, I feel that environmental protection in volcanic hazard areas is important.	Dunlap et al. (2000); Kaiser et al. (1999); contextualized to VR-based volcanic-eruption learning and the study context	[S] *Siri'* – responsibility for environmental protection	Deleted
Environmental care attitudes	KL5	*Setelah mengikuti simulasi VR, saya lebih peduli terhadap dampak lava, abu vulkanik, dan material erupsi lainnya terhadap lingkungan.*	After participating in the VR simulation, I care more about the impacts of lava, volcanic ash, and other eruption materials on the environment.	Dunlap et al. (2000); Kaiser et al. (1999); contextualized to VR-based volcanic-eruption learning and the study context	[P] *Pacce* – concern and ecological sensitivity	Retained
Environmental care attitudes	KL6	*Pengalaman VR mendorong saya untuk lebih memperhatikan hubungan antara bencana gunung api, kerusakan lingkungan, dan kehidupan masyarakat.*	The VR experience encourages me to pay greater attention to the relationship between volcanic disasters, environmental damage, and community life.	Dunlap et al. (2000); Kaiser et al. (1999); contextualized to VR-based volcanic-eruption learning and the study context	[P] *Pacce* – sensitivity to environmental and community impacts	Deleted
Environmental care attitudes	KL7	*Setelah menggunakan VR, saya merasa lebih terdorong untuk ikut menjaga lingkungan dari dampak yang dapat memperburuk kondisi setelah bencana gunung api.*	After using VR, I feel more motivated to help protect the environment from actions that may worsen conditions following a volcanic disaster.	Dunlap et al. (2000); Kaiser et al. (1999); contextualized to VR-based volcanic-eruption learning and the study context	[S] *Siri'* – responsibility and protective action	Deleted
Environmental care attitudes	KL8	*Setelah mengikuti simulasi VR, saya merasa lebih peka terhadap dampak lingkungan dan sosial yang dialami masyarakat di wilayah terdampak erupsi gunung api.*	After participating in the VR simulation, I feel more sensitive to the environmental and social impacts experienced by communities affected by volcanic eruptions.	Dunlap et al. (2000); Kaiser et al. (1999); contextualized to VR-based volcanic-eruption learning and the study context	[P] *Pacce* – empathy, sensitivity, and concern for affected communities	Retained
Environmental care attitudes	KL9	*Pembelajaran VR membuat saya semakin menyadari bahwa tindakan yang bertanggung jawab terhadap lingkungan dapat membantu mengurangi dampak bencana terhadap alam dan masyarakat.*	VR-based learning makes me more aware that environmentally responsible actions can help reduce the impacts of disasters on nature and communities.	Dunlap et al. (2000); Kaiser et al. (1999); contextualized to VR-based volcanic-eruption learning and the study context	[S+P] *Siri' Na Pacce* – responsibility, environmental care, and solidarity	Retained

APPENDIX B

Table B1. Concise indicator-decision audit

Code	Final decision	Reintroduced outer loading	Key diagnostic	Reason for deletion/retention
X5	Deleted	.797	SNP-VR-STEM–ECA HTMT = .905	Deleted because its inclusion resulted in an HTMT value above .90 between SNP-VR-STEM and ECA, indicating insufficient discriminant validity.
X6	Deleted	.790	Individual measurement criteria satisfied	Excluded as part of the selected reduced SNP-VR-STEM specification because the retained indicator configuration provided better overall discriminant validity while maintaining satisfactory reliability and convergent validity.
X7	Deleted	.874	Individual measurement criteria satisfied	Excluded as part of the selected reduced SNP-VR-STEM specification because the retained indicator configuration provided better overall discriminant validity while maintaining satisfactory reliability and convergent validity.
KE1	Retained	.613	CR = .858; AVE = .675	Retained to preserve substantive coverage of ecological awareness. Although its loading was below .708, the construct maintained satisfactory reliability and convergent validity.
KE4	Deleted	.903	Individual measurement criteria satisfied	Excluded as part of the selected reduced ecological-awareness specification to achieve clearer separation among the constructs while maintaining satisfactory reliability and convergent validity.
KE5	Deleted	.732	Other-construct loading = .822 on SNP-VR-STEM; EA–SNP-VR-STEM HTMT = .958	Deleted because it loaded more strongly on SNP-VR-STEM than on its assigned EA construct and the HTMT value exceeded .90, indicating construct overlap.
KE6	Deleted	.691	Other-construct loading = .762 on SNP-VR-STEM; EA–SNP-VR-STEM HTMT = .973	Deleted because its loading was below .708, its loading on SNP-VR-STEM exceeded its EA loading, and the HTMT value exceeded .90.
KE7	Deleted	.729	Other-construct loading = .772 on SNP-VR-STEM; EA–SNP-VR-STEM HTMT = .959	Deleted because it loaded more strongly on SNP-VR-STEM than on EA and the HTMT value exceeded .90, indicating insufficient construct separation.
KE8	Deleted	.720	Other-construct loading = .796 on SNP-VR-STEM; EA–SNP-VR-STEM HTMT = .980	Deleted because it loaded more strongly on SNP-VR-STEM than on EA and the HTMT value exceeded .90, indicating substantial construct overlap.
KE9	Deleted	.733	EA–ECA HTMT = .938	Deleted because its inclusion resulted in an EA–ECA HTMT value above .90, indicating insufficient discriminant validity.
KL1	Deleted	.762	EA–ECA HTMT = .902	Deleted because its inclusion resulted in an EA–ECA HTMT value above .90, indicating overlap between ecological awareness and environmental care attitudes.
KL2	Deleted	.817	Individual measurement criteria satisfied	Excluded as part of the selected reduced ECA specification because the retained indicator configuration provided better overall discriminant validity while maintaining satisfactory reliability and convergent validity.
KL3	Deleted	.804	Individual measurement criteria satisfied	Excluded as part of the selected reduced ECA specification because the retained indicator configuration provided better overall discriminant validity while maintaining satisfactory reliability and convergent validity.
KL4	Deleted	.792	Individual measurement criteria satisfied	Excluded as part of the selected reduced ECA specification because the retained indicator configuration provided better overall discriminant validity while maintaining satisfactory reliability and convergent validity.
KL6	Deleted	.817	Individual measurement criteria satisfied	Excluded as part of the selected reduced ECA specification because the retained indicator configuration provided better overall discriminant validity while maintaining satisfactory reliability and convergent validity.
KL7	Deleted	.867	Individual measurement criteria satisfied	Excluded as part of the selected reduced ECA specification because the retained indicator configuration provided better overall discriminant validity while maintaining satisfactory reliability and convergent validity.