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Research paper

Evaluating the Validity and Effectiveness of the Ethno-SSI Project–Integrated Virtual Reality in Improving Sustainable Environmental Literacy

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ABSTRACT

Integrating local cultural contexts into learning is essential for strengthening sustainable environmental literacy in support of SDG 4. Current chemistry education lacks a framework that synthesizes immersive technology with local cultural wisdom and Socio-Scientific Issues to foster sustainable environmental literacy. Thus, this study evaluates the validity and effectiveness of the Ethno-SSI Project–integrated Virtual Reality (VR) in enhancing students' sustainable environmental literacy regarding local wisdom on herbal tea and spices. A modified Plomp development model was employed. The outer model analysis showed satisfactory measurement quality, with outer loadings above 0.70, AVE values ranging from 0.508 to 0.732, and composite reliability and Cronbach's Alpha between 0.812 and 0.923. Discriminant validity was confirmed using the Fornell–Larcker criterion and cross-loadings, indicating that the measurement model was valid and reliable. Structural model results demonstrated that VR media significantly influenced students' knowledge (β = 0,471), attitudes (β = 0.672), and sustainability behavior (β = 0.462). The R^2 values indicated moderate contributions of VR media to attitudes (0.451), knowledge (0.222), and behavior (0.214), while model fit indices (SRMR < 0.08; NFI = 0.945) support the model's adequacy. The findings confirm that Ethno-SSI–Project integrated VR media is effective for strengthening sustainable environmental literacy through immersive, culturally grounded learning experiences. However, the absence of a control group, the single-course context, and the lack of longitudinal analysis limit causal interpretation and generalizability. Overall, the study demonstrates that Ethno-SSI–Project- VR is a valid, reliable, and high-impact pedagogical innovation for advancing sustainability literacy in contemporary science education.

Keywords: immersive VR, ethnoscience, social science issue, environmental literacy

In the 21st century, fostering sustainable environmental literacy has emerged as a global imperative due to increasing environmental degradation, public health issues, and the international framework established by the Sustainable Development Goals (SDGs) (Velempini, 2025), notably SDG 4 (Quality Education), SDG 3 (Good

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Health and Well-being), and SDG 13 (Climate Action). Environmental literacy is commonly understood as a multifaceted construct that includes knowledge, awareness, attitudes, and responsible environmental action (Jia & Wang, 2024). Nonetheless, numerous higher education practices persist in prioritizing abstract, decontextualized scientific information, thereby constraining students' capacity to relate scientific concepts to tangible environmental, cultural, and health-related challenges (Hanisch & Eirdosh, 2023; Kirchgasler, 2023).

Virtual Reality (VR) media has been widely applied in chemistry learning (Gnesdilow & Putambekar, 2025), offering immersive environments that enable students to interact with and explore complex scientific phenomena through interactive and experiential learning (Fombona-Pascual et al., 2022; Holly et al., 2021). Empirical research demonstrates that the use of virtual reality in science and environmental education improves students' conceptual comprehension, engagement, and academic performance via interactive, experiential learning (Chen & Chu, 2024; Matovu et al., 2023). Moreover, virtual reality enables the examination of environmental systems and sustainability issues that are challenging to see firsthand, while concurrently fostering environmental consciousness and pro-environmental behavior (Chen & Chen, 2024; Id et al., 2024; Papworth et al., 2024).

From an educational standpoint, methodologies that combine virtual reality with structured instructional techniques, such as the VR-assisted Smart Teaching Model, have demonstrated improvements in students' climate literacy and engagement with climate change (Tisoglu et al., 2024). Moreover, VR-based learning enhances critical thinking and digital literacy competencies within the frameworks of environmental and science education (Lee & Hwang, 2022; Maimatayeva et al., 2025). Additionally, immersive VR settings can enhance emotional engagement and cultivate a heightened understanding of environmental conservation (Spangenberger et al., 2024).

Despite these promising advancements, existing research on VR in education exhibits several critical limitations. First, most studies focus primarily on technological affordances and cognitive outcomes, with limited attention to affective and behavioral dimensions of sustainability learning (Makransky & Petersen, 2019). Second, VR-based learning environments are often developed using decontextualized or global content, neglecting the integration of local cultural knowledge systems (ethnoscience), which are essential for meaningful and culturally relevant learning. Third, VR applications are frequently implemented as isolated interventions without integration into comprehensive pedagogical frameworks, thereby limiting their long-term impact on sustainability competencies (Chiu & Lien, 2025).

The latest research focuses on integrating VR media technology with ethnoscience, resulting in the concept of Ethno-Virtual Reality (Ethno-VR) for herbal tea to support students in developing sustainable environmental literacy (Jangra et al., 2025; Zhang et al., 2024). The importance of this work is in creating Ethno-VR media about herbal spice tea to help chemistry students learn more about the environment in a way that will last. Although there is more and more research on using Virtual Reality (VR) in science and environmental education, most of it is on how to improve students' grasp of concepts, their interest in the subject, and their digital skills through content that is not tied to a specific setting or is more general (Boda & Brown, 2020; Shadiev et al., 2025).

There is still a significant gap in research because immersive VR technology, ethnoscience, socio-scientific issues (SSI), and project-based learning are not being used together within a single teaching framework to systematically improve environmental literacy across cognition, emotion, and behavior. Most studies examine these parts independently, leading to incomplete approaches that do not fully address the complexities of sustainability education. Also, culturally relevant practices such as traditional food, herbal medicine, and spice-based drinks are still not used enough as meaningful learning tools. Herbal spice tea is a good example, as it offers a rich ethnoscientific context that combines chemistry, health, and environmental sustainability. From a health perspective (SDG 3), herbal tea helps prevent disease and improve health; from an environmental perspective (SDG 13), sustainable farming helps protect biodiversity; and from an educational perspective (SDG 4), these settings offer real and meaningful learning opportunities.

The integration of local cultural knowledge (ethnoscience) and its explicit linkage to sustainable environmental literacy, particularly within chemistry education, remains limited (Ariyatun, Sudarmin, Wardani, et al., 2024; Purwasih et al., 2025). Consequently, the potential of VR to serve not only as a technological tool but also as a medium for cultural preservation and sustainability-oriented learning remains underexplored (Lorenzis et al., 2024). Meanwhile, research on herbal spice tea beverages has largely emphasized ethnobotanical, food science, and health-related perspectives (Estiasih et al., 2025; Novita et al., 2018), with limited attention to their pedagogical value as socio-scientific issues (SSI) in chemistry learning (Long et al., 2023). Existing ethnoscience-based learning approaches predominantly rely on conventional instructional media and lack immersive digital environments that engage students cognitively, emotionally, and culturally (Sudarmin et al., 2023; Zhang et al., 2024). Therefore, a clear research gap exists in the development of integrated learning media that combine

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ethnoscience, SSI, inquiry-based learning, and immersive VR technology to foster sustainable environmental literacy systematically (Jangra et al., 2025; Mafarja et al., 2025)

In this research, Ethno-VR media will be developed for the learning context of the Ethnoscience and Socio-scientific Issues (Ethno-SSI) integrated inquiry project on herbal tea to increase sustainable environmental literacy (Chen & Chu, 2024; Khoiri et al., 2021; Long et al., 2023). Herbal spice tea is chosen as the content and contextual foundation of the learning environment, since it has been an integral part of Indonesian culture for refreshment and therapeutic uses (Estiasih et al., 2025). Within this framework, herbal tea functions as a relevant socio-scientific issue (SSI), linking cultural traditions with health considerations and environmental sustainability (Carbone et al., 2025; Deha et al., 2024; Kong et al., 2024).

People believe that consuming herbal tea is beneficial for health, and this knowledge has been passed down from generation to generation. Analysis of various articles indicates that herbal tea offers several health benefits, including improving the immune system, supporting digestion, reducing stress (Novita et al., 2018), and preventing chronic diseases (Brimson et al., 2021). Meanwhile, another issue related to tea is the potential risks and health effects associated with its consumption (Das et al., 2017; Zhuang et al., 2022). Thus, it is important to provide Indonesian society, including students, with knowledge of tea and its culture, as well as its health benefits and risks, so that in the future they will be able to enjoy the benefits of herbal tea while minimizing its risks (Carbone et al., 2025; Thangavel et al., 2024).

Using spices as a learning context is urgent for fostering sustainable environmental literacy because they provide a culturally relevant and locally grounded entry point to connect scientific concepts with real-world ecological issues. Spices embody ecological, economic, and cultural values, making them effective for contextual and meaningful learning that enhances students' awareness, critical thinking, and responsible environmental behavior (Hartanti et al., 2024; Scherrer et al., 2023). Moreover, integrating spice-based contexts with innovative approaches such as project-based learning and technology-enhanced media can strengthen science literacy while promoting sustainability-oriented knowledge and practices (Sudarmin et al., 2026).

The differences in perspectives between traditional beliefs and scientific evidence regarding tea and its impacts on health, the environment, and resource sustainability emphasize the importance of integrating SSI into learning to develop critical thinking skills (López-Fernández et al., 2022), decision-making, and students' environmental responsibility (Högström et al., 2025; Viehmann et al., 2024). Therefore, learning that integrates ethnoscience, SSI, and immersive VR technology is expected not only to improve conceptual understanding but also to shape students' sustainable environmental literacy, particularly in terms of knowledge, awareness, attitudes, and responsible behavior towards environmental issues.

Nevertheless, previous studies have predominantly examined herbal tea from ethnobotanical or health perspectives, with limited exploration of its potential as a socio-scientific issue (SSI) within STEM education and sustainability learning. This represents a critical gap in connecting cultural practices, scientific literacy, and sustainability competencies within an integrated learning framework. Therefore, this study addresses these multiple research gaps by developing an integrated Ethno-Virtual Reality (Ethno-VR) learning model within an Ethno-STEM framework that combines immersive VR technology, ethnoscience, socio-scientific issues, and inquiry-based learning using herbal tea and spices as culturally embedded contexts.

This study offers a strong novelty by positioning Ethno-VR as a transformative pedagogical innovation that integrates immersive technology, cultural heritage, health awareness, and sustainability education. Unlike previous studies, this research systematically integrates Ethno-STEM, Ethno-SSI, and VR into a unified inquiry-based learning model to simultaneously enhance students' knowledge, attitudes, and sustainability behavior. This integrative approach represents a significant advancement in STEM education research and contributes directly to SDG 4, SDG 3, and SDG 13.

In this research, what is meant by sustainable environmental literacy referring to references (Ariyatun et al., 2024; Ridwan et al., 2021) is a form of student character to (1) understand related environmental knowledge, (2) awareness of the importance of the environment for life, (3) demonstrate a practical attitude towards protecting the environment, (4) skills in protecting the environment, (5) making decisions to preserve the environment, and (6) having sensitivity to the impact of an action on environmental risks. Research on tea and tea culture is interesting because tea culture is an important part of cultural heritage that must be preserved for its deep historical, social, and cultural value (Pan et al., 2022). The practice of ngeteh is not just about drinking tea; it also reflects the tradition of socializing, sharing stories, and building relationships among community members. Historically, the ritual of drinking tea has been an integral part of the culture of many societies worldwide, from China and Japan to England and Southeast Asia (Chang et al., 2014; Pan et al., 2022). Thus, preserving the ngeteh culture also means maintaining its values and ethics, such as politeness and honor in social interactions.

VR (Virtual Reality) enhances learning by providing immersive, interactive experiences, thereby improving engagement, motivation, and conceptual understanding. It allows for the simulation of complex environmental phenomena, which is beneficial for sustainability education. SSI (Socio-Scientific Issues) based learning

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encourages critical thinking and ethical reasoning, supporting environmental literacy and responsible decision-making. The integration of SSI aligns with sustainability competencies, such as systems thinking and anticipatory skills. Ethnoscience-based learning fosters relevance and student engagement by incorporating cultural knowledge, and evidence suggests that culturally responsive pedagogy enhances understanding and participation.

To mitigate this limitation, the integration of ethnoscience, socio-scientific issues (SSI), project-based learning, and virtual reality media has garnered heightened attention in science education. Ethnoscience facilitates the integration of local wisdom and indigenous knowledge into scientific education, enhancing its contextual relevance and significance (Zidny et al., 2020). Meanwhile, SSI-based learning promotes critical thinking, ethical reasoning, and decision-making by engaging students with real-world environmental and health issues (Ben-Horin et al., 2023; Herman et al., 2020). Research indicates that SSI-based approaches significantly enhance scientific literacy and environmental awareness (Kinslow et al., 2019). Project-based learning enhances environmental literacy and sustainability competencies through authentic, real-world engagement with environmental problems (Birdman et al., 2022).

This study combines various educational theories: Constructivism, Experiential Learning, the SSI Framework, and Sustainability Competencies. It proposes a conceptual framework where Ethno-VR, combined with an Ethno-SSI inquiry-based model within an Ethno-STEM perspective, serves as a primary factor influencing students' sustainable environmental literacy. The framework posits that immersive VR promotes experiential learning that simultaneously enriches cognitive, affective, and behavioral dimensions. It highlights ethnoscience and cultural contexts, using examples such as herbal tea and spices as mediators, while SSI enhances critical thinking and decision-making. Additionally, it establishes a hierarchy in which knowledge shapes attitudes, which in turn influence sustainable behaviors. This framework supports achieving Sustainable Development Goals (SDGs) 4, 3, and 13 through integrated STEM education.

This study aims to develop and evaluate VR media integrated into a project-based learning model using the Ethno-SSI approach on herbal spice tea. The research questions are: (a) RQ1: How does VR media integrated with the Ethno-SSI project influence students' sustainability knowledge? (b) RQ2: How does VR media integrated with the Ethno-SSI project influence students' sustainability attitudes? (c) RQ3: How does VR media integrated with the Ethno-SSI project influence students' sustainability behavior? The research hypotheses are formulated as follows: (a) H1: VR media integrated with the Ethno-SSI project has a positive and significant effect on students' sustainability knowledge, (b) H2: VR media integrated with the Ethno-SSI project has a positive and significant effect on students' sustainability attitudes, and (c) H3: VR media integrated with the Ethno-SSI project has a positive and significant effect on students' sustainability behavior.

The conceptual model in this study is structured as a systematic, iterative development framework comprising the concept, preparation, implementation, operational, real production, and evaluation phases. This framework is grounded in the integration of three main approaches—Socio-Scientific Issues (SSI), ethnoscience (Ethno-SSI), and Virtual Reality (VR)—which synergistically aim to enhance students' sustainable environmental literacy, SDG literacy, science–technology literacy, and conceptual understanding of spices (Bencze et al., 2020; Liu et al., 2019; Dewi et al., 2025). In the concept phase, the foundation of the learning design is established by identifying the instructional context, defining target learners, and formulating learning objectives. SSI is positioned as the pedagogical basis to foster critical, moral, and contextual reasoning through real-world environmental and socio-cultural issues (Bencze et al., 2020). The integration of ethnoscience strengthens this framework by linking local knowledge of spices with scientific concepts, while VR serves as an enabling technology that supports immersive, experiential learning (Liu et al., 2019).

The preparation phase translates these foundations into structured instructional design, including the development of Ethno-SSI inquiry project scenarios, VR-based learning environments, and visualization strategies for complex sustainability phenomena. This aligns with inquiry-based and contextually relevant learning principles that promote meaningful knowledge construction (González-Salamanca et al., 2020). The implementation phase represents the core iterative cycle—design, modeling, programming, and testing—through which the VR-based Ethno-SSI system is developed and refined. The embedded learning processes integrate inquiry, socio-scientific reasoning, and cultural contextualization, enabling active exploration of sustainability issues (Shutaleva, 2023).

In the operational phase, the system is enacted in authentic classroom settings, where students engage in problem identification, investigation, and solution development using VR as an interactive medium. Learning effectiveness is mediated by psychopedagogical factors such as cognitive engagement, emotional involvement, critical thinking, and environmental awareness, which are central to meaningful learning outcomes (González-Salamanca et al., 2020). The real production phase captures authentic student performance, reflecting their ability to integrate scientific knowledge, socio-cultural understanding, and sustainability practices aligned with the Sustainable Development Goals (SDGs) (Shutaleva, 2023).

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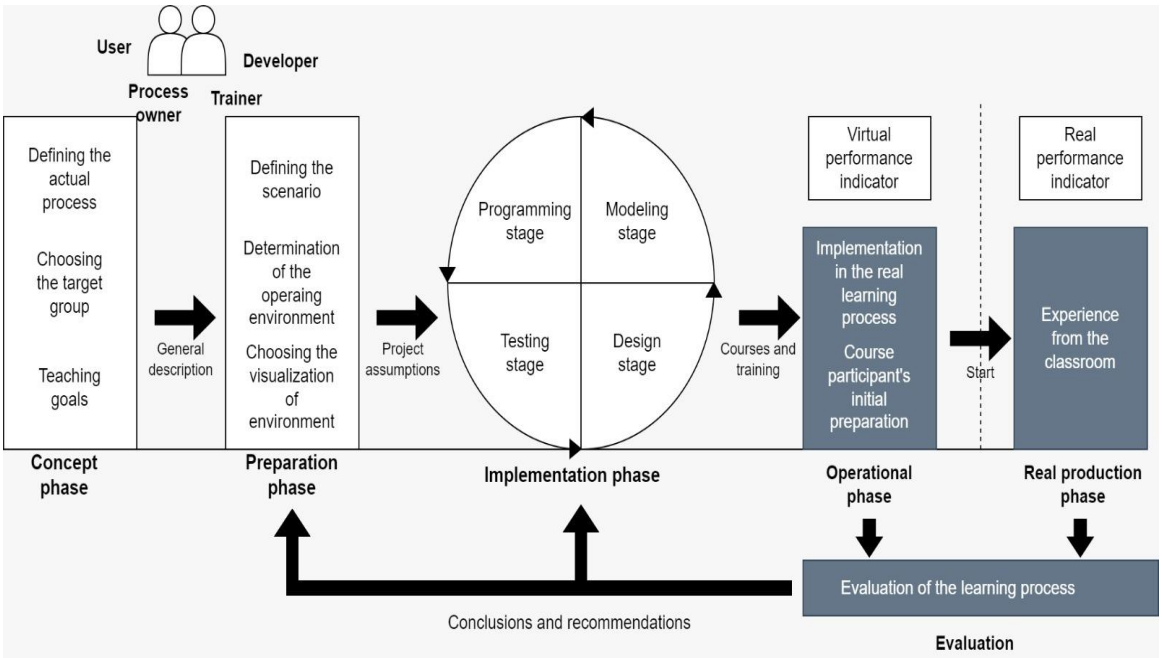
Finally, the evaluation phase is conducted iteratively to assess both process and outcome indicators, including environmental knowledge, attitudes, behavior, and broader literacy domains. The results inform the continuous refinement of earlier phases, emphasizing the model's cyclical nature. Thus, this conceptual framework establishes a coherent linkage between instructional design, immersive technology, and multidimensional learning outcomes, providing a theoretically grounded and empirically supported model for advancing holistic sustainability literacy in science education (Dewi et al., 2025). Figure 1 illustrates the proposed conceptual model as an iterative and phase-oriented framework that guides the design, development, implementation, and evaluation of Ethno-SSI inquiry projects integrated with Virtual Reality (VR), aiming to foster students' sustainable environmental literacy, SDG literacy, science–technology literacy, and conceptual understanding.

Figure 1

Conceptual model of ethno-SSI inquiry projects integrated with virtual reality (VR)



Based on Figure 1, the model presents a conceptual and developmental framework for Ethno-SSI–based learning integrated with Virtual Reality (VR), structured as a systematic, iterative cycle. In the concept phase, instructional needs are identified, including learning context, target learners, and objectives, forming the foundation for contextual and relevant learning design. This is followed by the preparation phase, where learning scenarios, operational environments, and visualization strategies are designed to guide system development.

The implementation phase involves an iterative cycle of design, modeling, programming, and testing, highlighting the dynamic and recursive nature of VR system development to ensure alignment with learning objectives. Subsequently, in the operational phase, the system is applied in real classroom settings, generating virtual performance indicators, while the real production phase captures authentic student experiences and outcomes as real performance indicators. Finally, the evaluation phase is conducted continuously to assess both virtual and real learning outcomes, producing conclusions and recommendations for improvement. Overall, the model is systemic, adaptive, and iterative, integrating instructional design, VR technology, and continuous evaluation to enhance the effectiveness of Ethno-SSI–based learning.

METHOD

Design or type of research

This study uses a Research and Development (R&D) design, with reference to the Plomp Development Model, which is modified to include an effectiveness test in the final stage. The Plomp model consists of three main phases: (1) Preliminary Research, (2) Prototyping Phase, and (3) Assessment Phase (Plomp & Nieveev, 2013). This design was chosen because it can produce learning media products that are valid, practical, and effective for strengthening sustainable environmental literacy. The product developed is in the form of Virtual Reality (VR) media integrated with the Ethno-SSI-Project approach on the topic of ethnoscience of herbal tea and spices. In addition to product development, this study also evaluates the validity of instrument constructs and media effectiveness using a quantitative approach based on Structural Equation Modeling-Partial Least Squares (SEM-PLS).

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Research procedure

The research procedure in this study was prepared following the development flow of the modified Plomp Model with the addition of an effectiveness test. The first stage is preliminary research, which includes analyzing learning needs, identifying student characteristics, reviewing the curriculum, and reviewing the literature on the ethnoscience of tea and spices to inform the preparation of Ethno-SSI-Project content. At this stage, local cultural data is collected, traditional knowledge is reconstructed into scientific concepts, and a VR-based analysis of the science-learning context is conducted.

The second stage is the prototyping phase, which begins with designing the media structure, developing VR visual scenarios, and integrating ethnoscience and SSI elements into the learning project's flow. Material, media, and education experts then validated the initial prototype. The validation results are used for revision and refinement until a final prototype is obtained that is suitable for testing.

The third stage is the assessment phase, which focuses on assessing the validity, practicality, and effectiveness of VR media. The test was carried out through a trial on chemistry education students who used media in learning activities. At this stage, the research not only collects quantitative data using SmartPLS 3.0 to analyze instruments, but also collects student perceptions through user responses to the VR learning experience.

Research sources and subjects

This study involved a sample of 126 active fifth-semester undergraduate students from the Chemistry Education and Environmental Science study programs at an Indonesian university. The sample consisted of students who had taken and passed the Conservation Education course in the previous odd semester. Therefore, students were assumed to have an adequate understanding of the concepts of sustainability, sustainable environmental literacy, and the Sustainable Development Goals (SDGs) targets, specifically SDG 3 (Health), SDG 4 (Education), and SDG 15 (Sustainable Environment), which align with the vision of their respective universities. Students' cognitive and emotional readiness to learn about sustainability issues is influenced by how well they understand them. Also, the pupils have already used Virtual Reality (VR) technology before. This experience increased their readiness and comfort in operating VR devices during the learning process. Students tended to adapt more quickly to VR interfaces and features, thereby minimizing technical obstacles during learning and focusing more on understanding the material, conceptual exploration, and active engagement in VR-based learning experiences.

The sampling process used a simple random sampling technique based on a defined sampling frame. The sampling frame consisted of all eligible fifth-semester students from both study programs who met the inclusion criteria, as verified through academic administrative records (N = 178). Eligibility was confirmed based on course completion, active academic status (not on academic leave), and non-participation in student exchange programs. Each eligible student was assigned a unique identification number, and the selection process was carried out using a computer-based randomization procedure (random number generation in Microsoft Excel). Participants were then selected randomly until the required sample size (n = 126) was achieved. This procedure ensured that each eligible student had an equal probability of being selected, thereby reducing selection bias.

Prior to participation, students completed a screening questionnaire to identify potential health conditions that could interfere with VR usage, such as severe visual impairment, dizziness, or sensitivity to immersive environments. Students who did not meet the health criteria were excluded and replaced using the same random selection procedure. This screening process was implemented to ensure participant safety and to minimize potential confounding variables that could affect learning performance and engagement during VR-based activities. Furthermore, the procedure enhances the study's internal validity by ensuring that all participants are physically capable of interacting optimally with the immersive learning environment. Ethical considerations were also strictly observed, with informed consent obtained from all participants prior to data collection, ensuring compliance with established research ethics standards.

The final sample consisted of students who met all inclusion criteria and none of the exclusion criteria, ensuring the appropriateness of the participants for VR-based learning activities. This rigorous selection process contributed to the homogeneity of the sample and reduced potential bias arising from health-related or technological limitations. In addition, it improved the dataset's internal consistency and enhanced the reliability of subsequent analyses. **Table 1** presents the demographic characteristics of the participants, including gender, age, and academic program, providing a comprehensive overview of the sample distribution and enabling a clearer interpretation of the study's findings.

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Table 1
Participants' Demographic Characteristics

Variable	Category	n	%
Gender	Female	87	69%
	Male	39	31%
Age	20 - 22 tahun	126	100%
Study Program	Chemistry Education	59	47%
	Environmental Science	67	53%
VR Exposure	Prior experience	126	100%
	No prior experience	0	-
Learning experience	Completed Conservation Course	126	100%

The semester-long study incorporated VR media, with structured documentation that ensured uniform participant exposure across 16 meetings and covered a range of learning activities. To ensure replicability, the implementation of the VR learning intervention integrated with the ethno-SSI project was explained in detail and in operational terms. The VR media was operated on laptops, allowing students to access the virtual environment via a screen (screen-based VR) without a head-mounted display (HMD). Each student used an individual laptop in a controlled classroom environment. The VR content was developed as a 360° interactive environment that integrated the ethnoscience context of herbal tea with socio-scientific issues, allowing students to explore, observe, and interact with representations of real-world phenomena.

The VR content was developed using the Spatial.io platform as a virtual "Indonesian Herbal Tea and Spice Museum," designed as an interactive 360° environment integrating ethnoscience perspectives and socio-scientific issues. The VR experience was non-immersive and accessed via a web-based interface without the use of head-mounted displays, aligning with accessible immersive learning approaches in education (Liu et al., 2019; González-Salamanca et al., 2020).

The virtual environment consisted of six thematic rooms. The first room presented the historical and cultural development of the use of herbal tea and spices in Indonesia through visual materials and explanatory videos, reflecting the integration of cultural knowledge into science learning (Dewi et al., 2025). The second room introduced various types of herbal teas derived from Indonesian plants, such as lemongrass, jasmine, rose, chamomile, eucalyptus leaves, and teak leaves, emphasizing traditional uses and ethnoscientific knowledge systems. The third room demonstrated traditional and modern processing methods, highlighting the transformation of raw materials into consumable products. The fourth room provided scientific explanations of chemical compounds, including bioactive substances and their health effects, supporting conceptual understanding in science education (Shutaleva, 2023). The fifth room presented cultural representations, such as batik motifs inspired by tea and spices, illustrating the integration of science and local culture within ethnoscience-based learning (Dewi et al., 2025).

The sixth room focused on socio-scientific issues by presenting a comparative discussion of herbal tea and other beverages, including health, environmental, and sustainability aspects such as production, consumption, and waste management. This approach fosters students' ability to analyze the interconnections among science, technology, society, and the environment (Bencze et al., 2020). The interactive VR environment enabled students to explore and analyze contextual phenomena grounded in local wisdom, thereby enhancing conceptual understanding, critical thinking, and evidence-based decision-making. Furthermore, this learning experience strengthened sustainable environmental literacy, including the ability to understand ecological systems, evaluate human impacts, and develop responsible solutions, contributing to sustainability-oriented education (González-Salamanca et al., 2020; Shutaleva, 2023), particularly in place-based STEM contexts where students' cultural identity is developed alongside scientific explanation (Chatmaneerungcharoen & Nielsen, 2025).

This Research, each learning session lasted approximately 100 minutes and consisted of three main stages: (1) an introductory stage (15 minutes), which included the presentation of learning objectives and technical guidance on using VR media; (2) a VR exploration and project-based activity stage (50 minutes), which allowed students to interact with the VR content and complete ethno-SSI project assignments; and (3) a reflection and discussion stage (35 minutes), which focused on critically discussing the exploration results and linking them to scientific concepts and sustainability issues.

The lecturer's role is to facilitate discussions, ensure effective use of VR media, and provide scaffolding during project activities. The lecturer develops a structured learning plan and implementation guide for each meeting to ensure consistent learning implementation. Learning implementation observations are conducted by trained observers to ensure all learning components are implemented according to the established design. The

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entire learning process is also systematically documented to ensure uniformity of presentation and the implementation of the learning sequence. This allows the intervention to be replicated in similar learning contexts.

The data collected consisted of quantitative post-test scores on environmental literacy and Likert-scale questionnaire responses measuring students' attitudes and behaviors toward sustainability. Informed consent was obtained from participants, and demographic data were safeguarded to control for variables. A sample size of 126 was justified for sufficient statistical power in PLS-SEM analysis (Memon et al., 2021), with proportional distribution to the population of each program.

The sample composition reveals a structurally homogeneous yet potentially biased dataset that strengthens internal validity while constraining broader generalizability. The pronounced gender imbalance (69% female) raises concerns regarding representational bias, particularly given evidence that technology engagement and immersive learning responses may vary across genders. At the same time, the complete uniformity in age (20–22 years), prior VR exposure, and completion of a conservation course suggests that the findings are derived from a cohort with relatively equivalent cognitive maturity, technological familiarity, and foundational sustainability knowledge, thereby minimizing extraneous variability and enhancing the precision of observed learning effects. However, this uniformity also limits the study's capacity to capture differential impacts across novice users or diverse demographic groups, potentially masking important variability in VR adoption and learning outcomes. Although the relatively balanced distribution between Chemistry Education and Environmental Science students offers some comparative analytical value in terms of disciplinary perspectives, the overall sample profile indicates that the results are most applicable to a pre-conditioned, technologically literate population rather than a fully representative educational context.

Data analysis instruments and techniques

The environmental literacy instrument in this study was developed based on three main components: sustainability knowledge, sustainability attitudes, and sustainability behavior (Gericke et al., 2018). Sustainability knowledge refers to an individual's ability to understand sustainability concepts, principles, and issues across environmental, social, and economic dimensions, including the impacts of human activities and the role of sustainable practices (Gong et al., 2026). Sustainability attitudes relate to environmental awareness, concern, and values, reflected in interest, sensitivity, and views on shared responsibility and equality (Sudarmin et al., 2025). Sustainability behavior, meanwhile, reflects concrete actions in implementing sustainability principles, such as participation, environmental stewardship skills, environmentally friendly behavior, and decision-making that considers impacts (Arantes, 2025).

These three parts are all part of environmental, social, and economic sustainability. The environmental aspect focuses on understanding, caring about, and acting on environmental issues. The social aspect focuses on participation and shared responsibility in society. The economic side focuses on making decisions and practices that are good for the economy in the long run. (Gericke et al., 2018). Sustainable environmental literacy, also known as references, is a way for students to (1) learn about environmental issues, (2) understand how important the environment is for life, (3) show that they care about protecting the environment, (4) learn how to protect the environment, (5) make choices that will help the environment, and (6) be aware of how their actions can affect environmental risks.

The instrument for assessing knowledge of sustainability comprises 10 essay questions on the environment, society, and the economy. A rubric that assesses conceptual compatibility, completeness of answers, and relevance to the desired context is used to rate each item on a scale of 1 to 5. A five-point Likert scale questionnaire is used to measure people's attitudes and behaviors toward sustainability. The scale goes from 1 (strongly disagree) to 5 (strongly agree). The total score for each component is the average of its item scores. A higher score indicates greater environmental literacy. The behavioral indicators were predominantly associated with environmental and social dimensions, while the economic dimension was not explicitly represented in this component.

Two experts validated the developed instrument, and the validation results were analyzed using Aiken's V index as a statistical measure of expert agreement on the relevance and quality of the instrument items (Kriswantoro et al., 2021; Tobón & Luna-Nemecio, 2021). The obtained Aiken V coefficients indicate high content validity across all items, reflecting strong expert consensus on their relevance and clarity. These results confirm that the instrument is conceptually aligned with the theoretical framework of sustainable environmental literacy and adequately represents its multidimensional constructs. Furthermore, the robustness of the validation findings supports the instrument's suitability for empirical application in assessing students' environmental sustainability literacy within VR-supported Ethno-SSI learning contexts, as presented in **Table 2**

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Table 2

Indicators of sustainability, environmental literacy, and results of Aiken's V content validity analysis

Literacy Components	Sustainability Aspects	Indicators	V Aikens	Criteria
Sustainability Knowledge	Environmental	Analyzing complex information to determine environmentally sustainable solutions in the production of herbal-spiced tea	0.80	Valid
		Identifying types of environmental pollution arising from herbal ingredient processing and analyzing solutions based on environmental contexts	0.70	Valid (Revision)
		Using scientific facts to explain the environmental impacts of herbal cultivation and climate change on herbal raw materials	0.85	Valid
		Analyzing causes and impacts of environmental pollution from herbal production and applying environmentally friendly practices	0.80	Valid
		Designing sustainable solutions to minimize environmental impact in herbal-spiced tea production	0.75	Valid (Revision)
	Social	Analyzing information on herbal-spiced tea production in relation to local wisdom and community practices	0.85	Valid
		Examining the role of government regulations and community participation in supporting sustainable herbal industries	0.75	Valid (Revision)
		Using evidence to propose solutions for sustainable herbal tea production based on local wisdom practices	0.80	Valid
	Economic	Analyzing the chemical composition and safety of natural herbal ingredients used in environmentally friendly tea products	0.75	Valid (Revision)
		Synthesizing information on market demand and global economic factors to maintain the quality and competitiveness of herbal spiced tea products	0.75	Valid (Revision)
Sustainability Attitudes	Environmental	Interest in the environment; sensitivity or concern for environmental issues	0.85	Valid
	Social	Attitudes toward gender equality and shared responsibility in protecting the environment	0.85	Valid
	Economic	Positive attitudes toward sustainable economic practices	0.75	Valid
Sustainability Behavior	Environmental	Being responsible for the environment	0.75	Valid (Revisio)
	Social	Locus of control	0.85	Valid
		Reflecting on one's role in local and global communities	0.85	Valid
		Evaluating and motivating actions in dealing with personal feelings and desires	0.72	Valid (Revision)

Data analysis was conducted using a quantitative approach. Quantitative data were analyzed using SmartPLS 3.0 software via Partial Least Squares Structural Equation Modeling (PLS-SEM) (Wong, 2015). The analysis began with the Outer Model test, including convergent validity (outer loadings and AVEs), discriminant validity (cross-loadings and Fornell–Larcker criteria), and construct reliability (Composite Reliability and Cronbach's Alpha) to ensure that the instruments used are valid and reliable. Furthermore, an Inner Model test was conducted to assess the effectiveness of the media on environmental literacy, using path coefficients, R^2, and effect size (f^2). The bootstrapping technique is used to test the significance of relationships between constructs.

The PLS-SEM analysis was conducted using post-test ratings derived from the environmental sustainability literacy questionnaire, integrating both essay-based responses to capture higher-order cognitive understanding of sustainability concepts and Likert-scale items (1 = strongly disagree to 5 = strongly agree) to measure attitudinal and behavioral dispositions. This mixed-format instrument design enhances construct coverage by combining cognitive depth with measurable latent traits, thereby aligning with multidimensional frameworks of sustainability

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literacy. Prior to model estimation, construct scores were computed by averaging item-level responses for each latent variable, a procedure that assumes indicator homogeneity and is appropriate for reflective measurement models.

Importantly, this integrative measurement approach constitutes a major strength of the study, as it enables a more comprehensive and nuanced capture of environmental sustainability literacy by simultaneously addressing cognitive, affective, and behavioral dimensions. The use of PLS-SEM further strengthens the analytical rigor by allowing the examination of complex, multivariate relationships among latent constructs, thereby providing robust explanatory and predictive insights into the underlying learning mechanisms. Moreover, the consistency of post-test data from a controlled VR-based intervention enhances the model's internal coherence, reducing measurement noise and increasing parameter stability. Collectively, these methodological choices substantially reinforce the validity, reliability, and explanatory power of the findings, positioning the results as empirically robust and theoretically grounded within the domain of sustainability education research.

RESULTS

Results of preliminary research

Learning needs analysis

Since its introduction in Europe in the 17th century, tea has become an integral part of everyday life, especially in countries such as England, Russia, and Portugal (Macfarlane & Macfarlane, 2024). Drinking tea for Javanese people is not only an activity of drinking, but also a means to build social relationships, meditation, and reflect on the simplicity of life (Haryono, 2013). In addition to examining the philosophy of tea-drinking culture across various countries, the analysis of learning needs shows that students need learning media that can connect local wisdom with modern scientific concepts in a more immersive, contextual way.

So far, learning about tea and spices has tended to be delivered theoretically through books or class discussions, so students have not gained direct experience that can describe the rich cultural values, scientific processes, and social-environmental issues inherent in the practice. The needs analysis also emphasizes that students' sustainable environmental literacy still needs strengthening, especially in understanding the relationship between cultural traditions and natural sustainability. However, without learning media that convey these values in concrete, engaging ways, students tend to see tradition only as a social activity, without understanding its scientific basis or sustainability. Therefore, integrating local wisdom on tea and spices into VR media based on the Ethno-SSI-Project is highly relevant to help students develop scientific perspectives, an attitude of environmental care, and behaviors that support sustainable development, in line with the goals of SDG 4.

Students' understanding of tea culture

In this research, before students carry out project-making activities regarding the creation of Ethno-VR project products based on Ethno-SSI, data collection is carried out through a questionnaire related to the understanding of tea, tea culture, how to make tea, the benefits of tea, the diversity of tea types, and tea as a global local wisdom. In this research, the questionnaire was distributed to 34 students enrolled in the Chemistry Learning Strategy course. The students' responses to the questionnaire were analyzed, and the results are presented in **Table 3.**

Table 3

Preliminary Data on Students' Perceptions of Tea and Spices

No	Item Questionnaire	Mean	SD
1	Tea and spice drinks are typical Indonesian and global beverages	4.52	0.48
2	Understanding the local and global diversity of tea and spice drinks	4.31	0.55
3	Understanding various local plants as herbal teas and spices	4.28	0.62
4	Understanding the use of tea and spice drinks as health beverages	4.47	0.50
5	Understanding the tea and spice drink-making process	4.25	0.59
6	Understanding that making tea and spice drinks involves scientific concepts	4.18	0.64
7	Understanding and getting to know other ingredients in tea and spice drinks, and their benefits	4.33	0.57
8	Students like to drink tea and spice drinks with added aroma, sweetener, sugar, or honey	4.40	0.52
9	Students are not familiar with the diversity of tea and spice drinks from various countries	2.10	0.81
10	Students' attitudes will preserve the culture of tea and spice drinks	2.35	0.77
11	Students are less interested in learning about tea and spice drink culture	4.38	0.54
	Average	3.96	0.60

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The results in Table 3 indicate a clear imbalance in students' environmental sustainability literacy, where strong cognitive achievement is not matched by affective and cultural development. High mean scores on items 1–7 (M = 4.18–4.52) confirm that students have well-developed conceptual understanding of tea and spice beverages, reflecting the effectiveness of the instructional design in supporting knowledge acquisition. However, the substantially lower scores on item 9 (M = 2.10) and item 10 (M = 2.35) reveal limited global awareness and weak cultural appreciation, suggesting that students' understanding remains locally bounded and lacks broader socio-cultural integration.

More critically, the contrast between high product preference (M = 4.40) and relatively high but shallow cultural interest (M = 4.38) indicates a dominant consumer-oriented perspective rather than a value-driven understanding of sustainability. This divergence highlights a key limitation of the intervention, where cognitive gains are not sufficiently translated into attitudinal and ethical transformation. Thus, while the results demonstrate strong knowledge outcomes, they simultaneously expose the need for more integrative learning approaches that explicitly connect scientific understanding with cultural values and sustainability ethics to achieve holistic environmental literacy.

Overall, this indicates that existing learning has not been able to integrate scientific knowledge, cultural awareness, and sustainability perspectives holistically, so learning innovations are needed that can bridge these three aspects. An Ethno-SSI-based learning approach integrated with Virtual Reality technology is relevant for providing a more immersive, contextually rich learning experience (Li & Wu, 2025; Purwasih et al., 2025). This approach has the potential to broaden students' global perspectives while fostering an appreciation for local culture and sustainability (Sudarmin et al., 2025). Several previous studies have also shown that integrating ethnoscience with technology-based media is effective in improving scientific and cultural literacy, as well as awareness of local wisdom (Verawati et al., 2025).

Results of prototyping

The design and development of Ethno-VR media in this study were carried out through a student-centered project approach that allowed students to creatively design virtual gallery spaces on the topic of herbal tea within an Ethno-SSI framework (**Figure 2**). After receiving technical training on VR media development from experts, students worked collaboratively in groups to determine project themes and develop Ethno-VR products that integrate local wisdom, scientific concepts, cultural values, and sustainability issues. The resulting Ethno-VR projects included virtual museums, mini towns, and interactive gallery rooms featuring tea and spice diversity, traditional and modern processing methods, visualizations of chemical compounds, cultural expressions, and socio-scientific controversies related to environmental sustainability.

Figure 2

Design of ethno-VR media: Indonesian herbal tea museum (https://www.youtube.com/watch?v=FQJbShTWPqA)

Evaluation by lecturers, peers, and students indicated that all Ethno-VR products were feasible, creative, and engaging, with well-organized content and immersive features. Student response analysis further showed that these Ethno-SSI–based Ethno-VR media effectively support and strengthen sustainable environmental literacy by connecting ethnoscience, real-life contexts, and environmental awareness through interactive and meaningful virtual learning experiences

Based on the Ethno-VR project, students developed immersive virtual environments that integrate ethnoscience, socio-scientific issues (SSI), and sustainable environmental literacy within interactive gallery and museum-like spaces centered on herbal tea. These environments incorporate multimodal elements—such as visual artefacts, videos, posters, interactive 3D objects, and culturally grounded scientific explanations—to guide users through coherent learning trajectories, including the history and biodiversity of tea, traditional and modern processing methods, chemical compound visualization, cultural practices, and sustainability challenges. Evaluation results from lecturers, peers, and students indicate that the Ethno-VR media demonstrate strong visual coherence, structured content organization, and meaningful interactivity, which collectively enhance

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conceptual understanding and foster critical awareness of sustainability. Overall, the findings highlight the potential of culturally contextualized virtual environments to bridge abstract scientific knowledge with real-world socio-cultural contexts, thereby supporting deeper and more transformative learning experiences.

Within the VR environment, locally contextualized herbal beverages—such as clove, cardamom, and lemongrass teas—are explicitly presented as learning objects to bridge scientific concepts with indigenous knowledge. This design not only introduces students to the ecological and biochemical properties of local spices but also embeds cultural relevance into the learning experience. By integrating these local tea variants, the VR setting serves as a pedagogical medium to cultivate sustainable environmental literacy, fostering students' awareness of biodiversity utilization, cultural preservation, and responsible consumption practices as part of sustainability-oriented character development.

Expert validation results

Validation of VR media content and language was conducted by three experts, who assessed feasibility, alignment with learning outcomes, and readability. Aiken's V values ranged from 0.78 to 0.89, indicating materials are generally 'quite relevant' to 'very relevant.' Most learning materials scored 0.89, indicating alignment with the learning objectives. High validity was also found for 3D objects and AR models, both scoring 0.89, although some elements need improvement. Language use was found to be effective, with all items rated between 0.78 and 0.89.

Media expert validation produced similar Aiken's V scores, affirming that interactivity and technical performance meet learning criteria. User Interface Design received a score of 0.89, reflecting good layout and navigation. Overall, the VR media's validity averaged 0.85, deeming it suitable for user trials with minor recommended revisions.

Results of the assessment phase – outer model analysis

Convergent validity and discriminant validity

The reliability test in this study was conducted using Composite Reliability and Cronbach's Alpha, both of which exceeded 0.6. Validity and reliability analysis model using SmartPLS via an external model test. For discriminant validity, cross-loadings are above 0.5, indicating that an indicator is more representative of its construct than any other indicator. In terms of reliability, internal consistency is indicated by Cronbach's Alpha and composite reliability, which ideally range from 0.6 to 0.7. All of these criteria provide basic guidelines in ensuring that the measurement model in SmartPLS meets statistical feasibility standards (Wong, 2013; Ghozali & Latan, 2015).

The study employed convergent validity tests using outer loadings and Average Variance Extracted (AVE). All indicators for the variables VR Media Implementation, Sustainability Knowledge, Sustainability Attitude, and Sustainability Behavior had values exceeding 0.70, confirming their effectiveness in representing their respective constructs. The outer loadings for VR Media Implementation ranged from 0.71 to 0.84, Sustainability Knowledge from 0.72 to 0.78, Sustainability Attitude from 0.70 to 0.76, and Sustainability Behavior also exceeded 0.70. Consequently, all indicators were retained, meeting the criteria for convergent validity, while the AVE values confirmed that the constructs exceeded the required threshold of 0.50, as shown in **Table 4**

Table 4

Measurement Model Reliability and Validity

Component	Cronbach's Alpha	rho_A	Composite Reliability	Average Variance Extracted (AVE)
Implementation of Ethno-SSI VR Media	0.978	0.979	0.979	0.613
Sustainability Knowledge	0.973	0.977	0.974	0.567
Sustainability Attitude	0.961	0.961	0.964	0.524
Sustainability Behavior	0.894	0.899	0.914	0.541

Cronbach's Alpha for all constructs is above 0.89, indicating excellent internal consistency for the instrument. The rho_A and Composite Reliability values also fall within 0.90–0.97, further supporting the conclusion that the indicators in each variable exhibit high stability and consistency. In terms of AVE, all constructs have values above 0.50, which range from 0.524 to 0.613. This value indicates that each construct explains more than 50% of the variance in its indicators, thereby meeting the criterion for convergent validity. It might also be helpful to explicitly state that an AVE value above 0.50 is typically considered a good indicator of convergent validity.

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Discriminant validity (Fornell–Larcker criterion)

To further assess discriminant validity, this study employed the Fornell–Larcker criterion, which compares the square root of the Average Variance Extracted (AVE) of each construct with the correlations between constructs. A construct is considered to have adequate discriminant validity when the square root of its AVE is greater than its correlations with other constructs.

As presented in **Table 5**, the diagonal values represent the square root of AVE, while the off-diagonal values indicate the correlations among latent constructs. The results show that all diagonal values (0.783 for VR, 0.753 for Knowledge, 0.724 for Attitude, and 0.736 for Behavior) are higher than the corresponding inter-construct correlations. This confirms that each construct shares more variance with its own indicators than with other constructs, thereby satisfying the Fornell–Larcker criterion and demonstrating adequate discriminant validity.

Table 5

Fornell–Larcker Criterion Matrix

Construct	VR	Knowledge	Attitude	Behavior
VR	0.783	0.471	0.672	0.462
Knowledge	0.471	0.753	0.484	0.413
Attitude	0.672	0.484	0.724	0.566
Behavior	0.462	0.413	0.566	0.736

Following the confirmation of convergent and discriminant validity, the structural model was evaluated to test the hypothesized relationships among constructs. Path coefficients (β) were examined to determine the strength and direction of the relationships, and the results are presented in **Table 6.**

Table 6

Path coefficients and correlation

Variable / Relationship	Path Coefficient (O)	Correlation (r)	Interpretation
Implementation of Ethno-SSI-Project VR → Sustainability Knowledge	0.471	0.471	Moderate direct effect; VR effectively increases students' knowledge about tea and herbal-spice sustainability.
Implementation of Ethno-SSI-Project VR → Sustainability Attitude	0.672	0.672	Strong direct effect; VR has the greatest impact on students' attitudes, shaping their appreciation for cultural and environmental aspects.
Implementation of Ethno-SSI-Project VR → Sustainability Behavior	0.462	0.462	Moderate to strong effect; students begin to translate knowledge and attitudes into pro-environmental behaviors.
Sustainability Knowledge → Sustainability Attitude	0.484	0.484	Moderate correlation; increased knowledge contributes to more positive environmental attitudes.
Sustainability Knowledge → Sustainability Behavior	0.413	0.413	Moderate correlation; knowledge partially influences behavior, supporting environmentally responsible actions.
Sustainability Attitude → Sustainability Behavior	0.566	0.566	Strong correlation: Attitude is a key mediator that translates learning into sustainable behavior.

The results indicate that the implementation of Ethno-SSI-Project integrated VR media has a significant positive effect on all sustainability dimensions. The strongest effect is observed on sustainability attitude (β = 0.672), followed by sustainability knowledge (β = 0.471) and sustainability behavior (β = 0.462).

In addition, sustainability knowledge shows a moderate relationship with both attitude (β = 0.484) and behavior (β = 0.413), while sustainability attitude has a strong influence on behavior (β = 0.566), indicating its important mediating role in translating knowledge into action.

Results of inner model test (media effectiveness)

The significance of the structural relationships was further evaluated using bootstrapping analysis. The results are presented in **Table 7.**

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Table 7

Bootstrapping Results Table

	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values
Implementation of Ethno-SSI-Project Integrated VR Media → Sustainability Knowledge	0.471	0.481	0.061	7.695	0.000
Implementation of Ethno-SSI-Project Integrated VR Media → Sustainability Attitude	0.672	0.676	0.067	9.985	0.000
Implementation of Ethno-SSI-Project Integrated VR Media → Sustainability Behavior	0.462	0.476	0.057	8.054	0.000

The results indicate that Ethno-SSI-Project integrated VR media has a significant positive effect on all sustainability dimensions. It improves sustainability knowledge with a coefficient of 0.471 and a t-value of 7.695, showcasing its effectiveness in immersive learning. The impact on attitudes is even stronger, with a coefficient of 0.672 and a t-value of 9.985, indicating heightened awareness and positive perceptions of sustainability. Additionally, sustainability behavior is positively influenced, as evidenced by a coefficient of 0.462 and a t-value of 8.054, suggesting a shift towards sustainable actions. This pattern suggests that the intervention is particularly effective in shaping affective dimensions, which are critical drivers of long-term behavioral change, while also maintaining substantial influence on cognitive and behavioral outcomes. The relatively similar coefficients for knowledge and behavior indicate a meaningful transfer from understanding to action, reflecting the transformative potential of the VR-based learning approach. Moreover, the consistently high t-values and stable confidence intervals confirm the precision and reliability of the estimates, reinforcing the robustness of the model. Overall, these results provide strong empirical evidence that the Ethno-SSI VR intervention effectively integrates cognitive, affective, and behavioral dimensions, aligning with the standards of high-impact sustainability education. **Table 8** presents the confidence intervals.

Table 8

Bootstrapping confidence interval

	Original Sample (O)	Sample Mean (M)	2.5%	97.5%
Implementation of Ethno-SSI-Project Integrated VR Media → Sustainability Knowledge	0.471	0.481	0.358	0.596
Implementation of Ethno-SSI-Project Integrated VR Media → Sustainability Attitude	0.672	0.676	0.531	0.792
Implementation of Ethno-SSI-Project Integrated VR Media → Sustainability Behavior	0.462	0.476	0.359	0.581

The confidence interval range that does not touch zero confirms that the influence is stable and trustworthy, giving confidence that the research findings are not the result of statistical chance (Nakagawa & Cuthill, 2007). The Ethno-SSI-Project using integrated VR media has proven effective in enhancing sustainable environmental literacy, significantly influencing attitudes, knowledge, and behavior. The immersive learning experiences shape perceptions and encourage positive behavior changes, aligning with SDG 4 (Quality Education) and SDG 13 (Climate Action). Confidence intervals (CIs) indicate a stable effect of VR on sustainability knowledge (0.358-0.596) and a substantial influence on sustainability attitudes (0.531-0.792). The influence on sustainability behavior, while slightly lower (0.359-0.581), remains consistent. The analysis confirms the effectiveness of VR-based learning interventions in fostering sustainable knowledge, attitudes, and behaviors among students.

In the Variant Analysis (R2) or Determination Test, which determines the magnitude of the influence or contribution of independent variables on the dependent variable, the value of the R-Square determination coefficient in the final Outer Model test is shown in **Table 9**.

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Table 9
R-Square Value

	R Square	R Square Adjusted	F Square
Sustainability Knowledge	0.222	0.216	0.285
Sustainability Attitude	0.451	0.447	0.823
Sustainability Behavior	0.214	0.208	0.273

The R-square values presented suggest that Ethno-SSI-Project's integrated VR media effectively influences sustainability variables. The R-square value indicates that VR media makes the greatest contribution to sustainability, while its influence on knowledge and behavior falls within the moderate but still meaningful range (Larner, 2014). The Sustainability Knowledge variable has an R-Square of 0.222, indicating that 22.2% of changes in knowledge can be attributed to VR use, marking a moderate impact. In contrast, the Sustainability Attitude variable shows a higher R-Square of 0.451, suggesting that nearly 45.1% of changes in attitudes are significantly influenced by VR media, correlating with previous research on immersive experiences. The Sustainability Behavior R-Square of 0.214 denotes that 21.4% of behavioral variation is influenced by VR, a moderate but notable contribution considering external factors.

The F-square values indicate that the effect size is strongest for sustainability attitude ($f^2 = 0.823$), suggesting a substantial contribution of the VR intervention to this construct. The model fit results are presented in **Table 10.**

Table 10
Output Model Fit Test

	Saturated Model	Estimated Model	Model-Fit Criteria
SRMR	0.067	0.079	SRMR<0.08
d_ULS	18.956	26.760	
d_G	1.301	1.301	
Chi-Square	835.723	835.723	
NFI	0.945	0.945	NFI>0.9

The fit test model results demonstrate that the model satisfies most feasibility criteria in the PLS-SEM analysis. The SRMR values for both models are below 0.08, indicating an acceptable level of covariance matrix mismatch. An NFI value of 0.945 further confirms the model's suitability, surpassing the 0.90 minimum.

DISCUSSION

The results of this study align with previous studies that found that VR technology can improve students' understanding through immersive visualization. Previous studies have shown that VR is effective in facilitating experiential learning, especially in environmental and science contexts (Cho & Park, 2023) Several studies explain that virtual field trip-based learning can strengthen ecological concepts, increase empathy for environmental issues, and help students understand the relationship between natural phenomena and human actions (Billinghurst et al., 2014; Elmqaddem, 2019).

The findings in this study strengthen this conclusion by adding a new context: the integration of VR with the Ethno-SSI-Project approach, so that the learning experience is not only visual and exploratory but also rich in cultural value and relevant to real life. These findings align with previous studies that affirm that cultural products, such as tea, can be an effective gateway to developing science literacy while strengthening cultural identity (Brown, 2017; Sudarmin et al., 2024). This condition underscores the urgency of using Virtual Reality-based media to overcome the limitations of field access and offer a richer exploratory experience (Chiu & Lien, 2025).

However, some important aspects still seem to need strengthening. The data show that students are unfamiliar with the diversity of the world's tea cultures and lack a strong commitment to preserving them. Their awareness focuses more on aspects of consumption, such as a preference for flavored or sweet tea, rather than on the cultural, historical, and ecological significance of the tea-drinking tradition. These findings reflect a pattern also widely observed in other studies, in which younger generations tend to adopt tea-drinking culture as a modern lifestyle but lack an understanding of its philosophical and historical value (Yu & Huang, 2024). Several cross-cultural studies, including research on Japanese, Chinese, British, and Javanese tea traditions, show that drinking tea is not only a consumptive activity but also embodies values such as harmony, simplicity, contemplation, and ecological wisdom (Pan et al., 2022; Shen, 2023). This gap indicates a disconnect between experiential engagement and cultural literacy, suggesting that current learning interventions may insufficiently

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integrate socio-cultural depth into sustainability education. Consequently, strengthening culturally embedded and reflective learning components is essential to transforming consumption-oriented awareness into a value-driven understanding of sustainability.

These results further confirm the relevance of developing SSI-based Ethno-VR media that offer a holistic learning experience that combines cultural contexts, scientific processes, and sustainability issues. Various previous studies have shown that ethnoscience-based media and immersive technologies, such as VR, are effective in increasing cultural literacy, science literacy, and environmental care (Liu et al., 2019). Studies in science education also confirm that the SSI approach fosters a more critical understanding of the relationships among culture, science, and society (Bencze et al., 2020). Therefore, integrating VR into the Ethno-SSI-Project can significantly enrich students' insights into tea culture while fostering ecological awareness and sustainability (Dewi et al., 2025). Taken together, these findings underscore the transformative potential of Ethno-SSI VR as an innovative pedagogical framework that not only advances multidimensional literacy but also cultivates deeply rooted sustainability values, thereby positioning it as a high-impact approach within contemporary science education research.

The results of the preliminary research show a real need to develop learning media that not only convey information but also foster transformative learning experiences. The initial findings, combined with support from previous research, provide a strong foundation for the development of the Ethno-SSI-Project's integrated VR media, which has great potential to improve students' cultural understanding, science literacy, and sustainability attitudes. The success of students in presenting various content through a combination of text, photos, videos, 3D models, music, and cultural narratives shows that multimodal learning can improve understanding and create a more meaningful learning experience (Giannakos, 2020; Giannakos et al., 2019).

The findings of this study show that Ethno-VR based on Ethno-SSI not only serves as an innovative learning medium but also effectively strengthens sustainable environmental literacy. This media provides a space for students to develop creativity, connect science with local culture, and understand environmental issues through immersive experiences. The high validity of the media indicates that the developed product has strong potential for implementation in modern science learning. This approach aligns with the needs of 21st-century education, which emphasize creativity, critical thinking, technological literacy, and environmental sustainability (González-Salamanca et al., 2020; Shutaleva, 2023).

The results section shows that the measurement and structural models used in this study meet all necessary statistical criteria, providing a solid basis for concluding that the Ethno-SSI-Project integrated VR media are effective. From the aspect of the outer model, all indicators show excellent convergent and discriminant validity. An outer loading value above 0.70 indicates that each indicator accurately represents its construct. AVE values that exceed the 0.50 limit confirm that each construct adequately describes the proportions of the indicator's variance (Cheung et al., 2024; Haji-Othman & Yusuff, 2022). In addition, the high internal consistency of Cronbach's Alpha, rho_A, and composite reliability indicates strong stability and reliability (Izah et al., 2024). The discriminant validity, as assessed by the Fornell-Larcker test and cross-loadings, also confirmed that the entire construct was correctly positioned without overlap, indicating that the measurement model was of very good quality (Haji-Othman & Yusuff, 2022).

The results suggest that the Ethno-SSI-Project, which integrated VR media focused on tea and herbal-spice topics, is effective in fostering sustainable environmental literacy. These findings are in line with the theoretical framework, which posits that behavioral changes usually occur after the formation of strong understanding and attitudes, so that the most significant effect on affective aspects is theoretically acceptable outcomes (Agarwal & Malhotra, 2005). Among the three dimensions, attitudes are most strongly influenced, followed by knowledge and behavior. This aligns with educational theories that immersive and interactive learning experiences first shape perception and attitudes, which then encourage knowledge acquisition and behavioral change.

The positive outcomes highlight the potential of Ethno-VR to support SDG 4 (Quality Education) by providing meaningful, culturally grounded learning experiences, and SDG 13 (Climate Action/Environmental Sustainability) by promoting pro-environmental literacy and behavior, particularly by fostering understanding of the ecological and cultural importance of tea and spice consumption. Ethno-SSI-Project's integrated VR media is an effective learning approach not only for improving students' understanding of sustainability but also for shaping positive attitudes and behaviors toward sustainability. Strong statistical support from measurement and structural models indicates that VR-based interventions can provide immersive, contextual, and impactful learning experiences. These findings confirm that integrating VR technology with ethnoscience approaches and socio-scientific issues offers significant potential as a learning strategy relevant to the demands of modern education, especially for strengthening sustainability literacy.

A key implication of the study is the need for an integrated, systems-thinking approach to the Sustainable Development Goals (SDGs), emphasizing the interdependence of global challenges. The integration of Virtual Reality (VR), Ethno-Scientific Social Issues (Ethno-SSI) oriented towards STEM, and culturally relevant contexts

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like tea and rempah creates a comprehensive learning environment that addresses multiple SDGs simultaneously, particularly SDG 4 (Quality Education), SDG 3 (Good Health and Well-being), and SDG 13 (Climate Action). This integrative framework not only enhances conceptual understanding but also facilitates the development of cross-cutting competencies, enabling learners to perceive sustainability as a dynamic and interconnected system of knowledge, values, and actions. Consequently, the study advances a transformative pedagogical paradigm in which culturally responsive and technology-enhanced learning catalyzes aligning educational outcomes with global sustainability agendas at both local and global scales.

From the perspective of SDG 4, VR provides immersive learning experiences that boost student engagement and understanding, as evidenced by a systematic review indicating improvements in learning outcomes and motivation in higher education. VR enhances experiential, student-centered learning, which is vital for fostering higher-order thinking skills. Regarding SDG 3, incorporating tea into a socio-scientific context fosters health literacy and preventive awareness, allowing students to grasp the impact of lifestyle choices on well-being. This approach aligns with the preventive health education goals of SDG 3. In the context of SDG 13, the focus on rempah helps clarify environmental sustainability and biodiversity conservation. VR simulations facilitate exploration of the environmental impacts of agriculture, enhancing awareness of climate-related issues and promoting behavioral change through relatable, immersive experiences.

This study makes a significant contribution by integrating Socio-Scientific Issues (SSI), ethnoscience (Ethno-SSI), and Virtual Reality (VR) into an inquiry-based project learning framework. This integration not only enhances the contextual and cultural relevance of science learning particularly in the domain of herbal and spice-based knowledge—but also promotes a systems-thinking perspective. Through this approach, students are encouraged to analyze the interconnections among environmental sustainability, socio-cultural practices, and technological applications, which are essential for addressing complex global challenges.

Furthermore, the use of immersive VR environments, combined with Ethno-SSI inquiry projects, enables students to engage in authentic problem-solving situations actively. This design supports the development of multiple competencies simultaneously, including sustainable environmental literacy, SDG literacy, science–technology literacy, and conceptual understanding. The model's phase-based, iterative structure also enhances its practical applicability, ensuring alignment among instructional design, implementation, and evaluation.

However, several limitations should be acknowledged. Methodologically, this study employed a PLS-SEM-based structural model without incorporating a pre-test–post-test experimental design or a control group, which constrains the ability to draw strong causal inferences and instead emphasizes predictive relationships (Bencze et al., 2020). As a result, the findings primarily indicate associations rather than definitive causal effects between the Ethno-SSI inquiry projects integrated with VR and the targeted literacy outcomes. In addition, the relatively small sample size and the single-course context limit the generalizability of the findings to broader educational settings, particularly those with more diverse learner characteristics (González-Salamanca et al., 2020).

From a practical perspective, the implementation of VR-based learning depends heavily on the availability of technological infrastructure, which may not be equally accessible across institutions, especially in resource-constrained contexts (Liu et al., 2019). Moreover, the ethnoscience component is inherently context-specific, requiring careful cultural adaptation when applied to different socio-cultural environments (Dewi et al., 2025). Finally, this study did not examine the long-term impact of the intervention, particularly on sustained behavioral change and environmental responsibility, thereby limiting the ability to confirm the longitudinal effectiveness of the learning model (Shutaleva, 2023). These limitations highlight the need for future research employing more rigorous experimental designs, larger and more diverse samples, and longitudinal approaches to strengthen causal claims and extend the applicability of Ethno-SSI VR-based learning frameworks.

Therefore, future research is recommended to employ quasi-experimental or experimental designs with control groups, pre-test and post-test measurements, and involve larger samples across institutions to more robustly test the causal impact of Ethno-VR media on sustainability knowledge, attitudes, and behavior. Future research should also explore the implementation of Ethno-VR media in various science topics and cultural contexts, such as food sustainability, biodiversity, and climate change, to test the model's consistent effectiveness in improving sustainability literacy. Longitudinal studies that observe changes in student attitudes and behavior over time are also needed to ensure that VR-based immersive learning experiences not only impact immediate understanding but also shape lasting, sustainable behavior.

CONCLUSIONS

The study demonstrates that the Ethno-SSI-Project's integrated VR media enhances students' knowledge, attitudes, and behaviors regarding sustainable environmental literacy, particularly through local wisdom on tea and spices. Preliminary research highlighted the need for immersive education rooted in local culture, leading students to create engaging Ethno-VR products. Validity and reliability tests confirmed the robustness of the instruments used, with significant impact on sustainability knowledge ($\beta = 0.471$), attitudes ($\beta = 0.672$), and

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behavior (β = 0.462). The approach aligns with educational needs by merging immersive technology with ethnoscience, fostering critical thinking and environmental awareness. It supports SDG 4 (Quality Education) and SDG 13 (Climate Action), making Ethno-SSI-Project-based VR media a viable solution for integrating local knowledge and technology in education while promoting sustainability literacy. These findings affirm that integrating VR and Ethno-SSI is both pedagogically effective and theoretically grounded in transformative sustainability education. The stronger impact on attitudes highlights the capacity of immersive, culturally contextualized learning to shape values and environmental awareness, while the consistent effects on knowledge and behavior indicate a meaningful translation into sustainable practices. Thus, this approach represents a scalable, high-impact framework for advancing holistic sustainability literacy by integrating local wisdom and technology-enhanced learning.

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Ethical statement

Ethical considerations were carefully observed throughout the study. Prior to participation, students received a clear explanation regarding the research objectives, procedures, and the use of collected data for research purposes. Participation was entirely voluntary, and informed consent was obtained from all participants without coercion. Students were informed that their academic evaluation would not be affected by their decision to participate or withdraw from the study. All participant data were anonymized and treated confidentially.

Competing interests

The authors declare no conflict of interest.

Author contributions

Sudarmin contributed to the research conceptualization, data collection, analysis and interpretation, and manuscript writing. Ariyatun contributed to manuscript writing, critical revision, and final approval. Anna Permanasari contributed to data analysis, critical revision, and final approval. Edy Hafizan Mohd Shahali contributed to data collection and analysis. Rr. Sri Endang Pujiastuti contributed to data collection and critical revision. Dwi Septiana Sari contributed to data analysis and manuscript writing. Henie Poerwandar Asmaningrum contributed to data collection and analysis. All authors approved the final version of the manuscript.

Data availability

The datasets supporting the results of this study can be obtained from the corresponding author upon reasonable request.

AI disclosure

The authors used artificial intelligence (AI)-assisted tools, including OpenAI's ChatGPT, solely for language refinement, grammar checking, and improving the readability of the manuscript. All conceptual development, data analysis, interpretation of findings, and final manuscript decisions were conducted entirely by the authors. The authors take full responsibility for the content of this manuscript.

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