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Utilization of virtual reality as a learning tool to increase students' pro-environmental behavior at universities: A maximum likelihood estimation approach

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Abstract

This research explores the effect of virtual reality technology on enhancing university students' environmental knowledge (ENK), environmental attitudes (ENAs), and pro-environmental behaviors (PEBs). The primary objective is to evaluate how immersive virtual reality (VR) experiences influence students' understanding of pressing environmental issues like climate change, deforestation, and pollution. A sample of 336 students from Universitas Negeri Makassar who participated in a VR-based environmental education class were surveyed through structured questionnaires distributed via Google Forms. Stratified random sampling was employed to ensure a diverse illustration of the student population. The study applies covariance-based structural equation modeling using the AMOS program to evaluate the correlations among the variables of ENK, attitudes, and behaviors. The results indicate that VR significantly enhances students' ENK by providing an interactive and immersive learning platform that simplifies complex ecological concepts. VR was shown to positively influence students' ENAs by simulating real-world environmental degradation consequences, fostering emotional connection and concern. A robust link was also identified between improved ENAs and increased PEBs, such as waste reduction and energy saving. These findings demonstrate that VR can be an actual tool for driving behavioral change in the context of environmental education, offering a promising approach to addressing global sustainability challenges. The analysis adds to the expanding body of literature on technology-enhanced learning, highlighting the potential of VR to promote sustainability through education and fostering a more profound commitment to environmental stewardship among students.

Keywords: conservation awareness, ecological interventions, environmental education, sustainable environmental education, learning technology

INTRODUCTION

Climate change, pollution, and environmental degradation present increasingly urgent global challenges that we must address (Stanikzai et al., 2024). Human activities, particularly greenhouse gas emissions, have led to a rise in global heat, resulting in severe consequences for ecosystems and human life worldwide (Fang et al., 2011; Makkasau & Sahabuddin, 2023; Mikhaylov et al., 2020; Yue & Gao, 2018). The United Nations environment program highlights that environmental degradation, including biodiversity loss, continues to worsen and requires a collective effort from all levels of society, including the younger generation, who will face its impacts (Alshaybani et al., 2024; Basri et al., 2015; Nicolaides, 2006; Ventabal et al., 2024). Educational institutions strategically prepare students as environmentally conscious agents of change who can implement sustainable solutions (Nicolaides, 2006; Oe et al., 2022; Tilbury, 2004).

Information and communication technologies have strengthened educational efforts, including environmental education. One technology that has gained attention is virtual reality (VR), which allows users to experience immersive and interactive learning.

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Contribution to the literature

- Virtual reality technology (VRT) significantly enhances environmental attitudes (ENAs), knowledge, and behavior, reinforcing previous research findings with more in-depth quantitative evidence.
- VRT has been proven to foster empathy and reduce psychological distance toward environmental issues, motivating pro-environmental behavior (PEB) by providing immersive, emotional, and realistic experiences.
- This study provides empirical evidence that can be used to design more effective environmental education programs and policies, utilizing VR technology to raise ecological awareness and knowledge in society.

This technology enables students to see and feel the impact of various environmental issues, such as deforestation, water contamination, and global warming, more realistically and engagingly (Breves & Greussing, 2021; Calil et al., 2021). Ahn et al. (2015) demonstrate that using VR in environmental education can enhance students' empathy and responsiveness to ecological issues, thus encouraging them to adopt more environmentally friendly. Immersive learning experiences through VR can increase students' emotional and cognitive engagement, promoting pro-environmental attitudes and behavior changes (Markowitz et al., 2018).

VR shows excellent potential to expand knowledge and enhance student awareness of environmental issues (Fernandez, 2017; Zhang et al., 2020a). It allows students to experience challenging or impossible real-life situations, such as witnessing polar ice melting or tracking plastic waste through the ocean. Interactive approaches like VR are crucial for improving understanding of environmental issues and promoting sustainable behavior changes (Markowitz & Bailenson, 2021; Rambach et al., 2021). The use of virtual experiments to evaluate ecological policy was introduced (Fiore et al., 2009), which showed that virtual experiences could significantly reduce judgment errors. Their study involved virtual simulations of forest fires, leading participants to beliefs more aligned with actual risks and reducing discrepancies between perceived and real-world dangers. This foundational study paved the way for further research into the impacts of low-immersive simulated ecosystems on environmental behavior and policy support (Matthews et al., 2017; Olschewski et al., 2012).

Several studies suggest that immersive storytelling within VR can significantly enhance concern and risk perception related to environmental challenges (Breves & Schramm, 2019; Chirico et al., 2023; Markowitz et al., 2018). Immersive VR experiences create a sense of presence–the psychological state of "being there"–amplifying emotional commitment to the virtual environment (Baños et al., 1999). This heightened sense of presence allows users to interact more vividly with environmental scenarios, leading to greater awareness and empathy toward ecological issues. In the study by Ahn et al. (2014), participants experienced the virtual act of cutting down a tree, which increased self-reported concern about deforestation. Similarly, Chirico and Gaggioli (2019) showed that virtual experiences of natural environments evoked more robust emotional responses than real-world counterparts, potentially due to VR-controlled, immersive, and interactive nature.

These immersive experiences increase emotional engagement and foster a deeper cognitive connection between users and nature. This connection is crucial, as it may trigger shifts in ENAs, often translating into tangible PEBs (Ahn et al., 2016; Breves & Heber, 2020). For instance, Nelson et al. (2020) found that users who experienced immersive VR content that highlighted environmental degradation were likelier to donate to environmental organizations, reflecting a clear link between virtual experiences and real-world actions. Other studies, such as those by Soliman et al. (2017), indicate that VR immersive nature increases participants' willingness to engage in sustainable practices, such as recycling or energy saving, by making the concerns of conservation harm feel more immediate and personal.

In addition to influencing behavior, VR can potentially manipulate psychological distance, which refers to how distant or abstract an issue feels to an individual (Liberman, 2014). Environmental problems, such as climate change or deforestation, are often perceived as temporally or spatially distant, reducing people's urgency to act (van der Linden, 2015). However, VR can effectively shrink this psychological distance by providing an immersive, first-person perspective that simulates direct interaction with environmental problems (Ahn et al., 2016). When virtual environments feel sufficiently "real," participants may treat the simulated scenarios as genuine experiences (Fiore et al., 2009). Markowitz et al. (2018) demonstrated that participants who virtually explored environments impacted by climate change exhibited heightened risk perceptions, feeling a greater responsibility to mitigate these issues. Breves and Schramm (2021) further illustrated that the spatial presence created in immersive VR can reduce the psychological distance between individuals and environmental risks, making abstract problems like rising sea levels or species extinction feel more immediate and urgent.

This reduction in psychological distance is not solely a matter of spatial or temporal proximity; it also pertains to the social and experiential distance from environmental issues. By placing users in scenarios where they can vividly "experience" the impacts of climate change or habitat loss, VR makes it easier for individuals to relate to the victims of environmental harm, whether humans, animals, or ecosystems (Schuldt et al., 2018). This experiential immersion may increase feelings of personal responsibility and the belief that individual actions can make a difference (Sanders et al., 2021). Additionally, research suggests that reducing psychological distance through VR can enhance both the affective (emotional) and cognitive (knowledge-based) dimensions of environmental concern, leading to stronger behavioral intentions (Baños et al., 2012; Soliman et al., 2017).

The combination of emotional resonance, cognitive engagement, and reduced psychological distance provided by immersive VR technologies has transformative potential for environmental education and advocacy. By enabling individuals to interact with virtual representations of ecological crises in a controlled yet impactful manner, VR may be a powerful tool to cultivate PEBs on a larger scale (Nelson et al., 2020). Furthermore, as VR technology evolves, its applications in environmental policy-making, conservation efforts, and public awareness campaigns will likely expand, making it a pivotal medium for shaping personal and collective responses to global ecological challenges (Slapakova et al., 2024).

VRT in environmental education promises to revolutionize how students comprehend environmental issues and respond to and act on ecological challenges. VR offers an immersive and interactive learning experience, creating virtual environments where students can observe, participate, and feel the impact of human behavior on ecosystems (Liu et al., 2020). This experience provides a significant advantage over more theoretical and often less engaging conventional teaching methods. Through VR, students not only learn complex environmental concepts but also gain the opportunity to experience the deep interconnectedness between human activities and their ecological impacts in a tangible way (Makransky & Lilleholt, 2018).

Makransky et al. (2019) found that interactive VR enhances students' critical understanding of environmental issues. Meanwhile, Shin (2018) highlights the importance of emotional engagement in VR experiences to strengthen ecological knowledge and awareness. VR is an informative educational tool and a catalyst for changing pro-environmental attitudes and behaviors. This study explores and evaluates the impact of using VR to enhance students' knowledge, attitudes, and PEBs. This research assesses VR's effectiveness in transforming environmental understanding, influencing attitudes, and encouraging actions supporting sustainability.

LITERATURE REVIEW AND DEVELOPMENT HYPOTHESIS

Virtual Reality Technology for Education

VR has become a groundbreaking educational tool, providing immersive and interactive 3D experiences that significantly augment learning (Cooper et al., 2019; Hamilton et al., 2021; Mulders et al., 2020). As a disruptive technology, VR can revolutionize education, much like how the Internet reshaped daily life (Rosedale, 2017). Its effectiveness relies on the seamless integration of user interaction, visual and auditory immersion, and culturally adaptive VR environments (Damala et al., 2013; Gao et al., 2021; Sutcliffe et al., 2005). By enabling users to navigate across time and space, VR allows learners to engage directly with real-world scenarios, facilitating strategy evaluation and problem-solving (Scurati et al., 2021). The advent of technologies like 5G will further amplify VR's role in education by enhancing student motivation and improving learning outcomes (Huang & Liao, 2015). VR enhances learning outcomes in medicine and engineering by offering interactive, risk-free environments that optimize training resources (Pensieri & Pennacchini, 2014; Zhao & Lucas, 2015). By promoting experiential and situational learning, VR fosters higher student engagement and task performance levels than traditional methods (Dinis et al., 2017; Salah et al., 2019).

In environmental education, VR significantly benefits by creating realistic, impactful learning experiences. Early studies showed that simulations improve learners' perceptions of real-world risks by aligning virtual experiences with actual environmental challenges (Bateman et al., 2009; Fiore et al., 2009). More recent research emphasizes the importance of high-immersion VR environments, which significantly increase user engagement and concern for ecological issues (Ahn et al., 2016; Innocenti, 2017). For instance, immersive VR storytelling and interactive experiences, such as simulating the cutting down of a tree, deepen learners' understanding and emotional connection to environmental concerns (Chirico et al., 2017; Markowitz et al., 2018). These immersive experiences generate a heightened sense of presence, reduce psychological distance, and encourage more significant ecological action and advocacy (Breves & Schramm, 2021). VR's ability to make abstract concepts concrete enhances its educational effectiveness, particularly in promoting environmental awareness and fostering behavioral change (**Figure 1**).

Environmental education aims to develop the awareness, knowledge, attitudes, and behaviors necessary for sustainable living (Stevenson, 2007; Stevenson et al., 2013). Fostering positive ENAs is

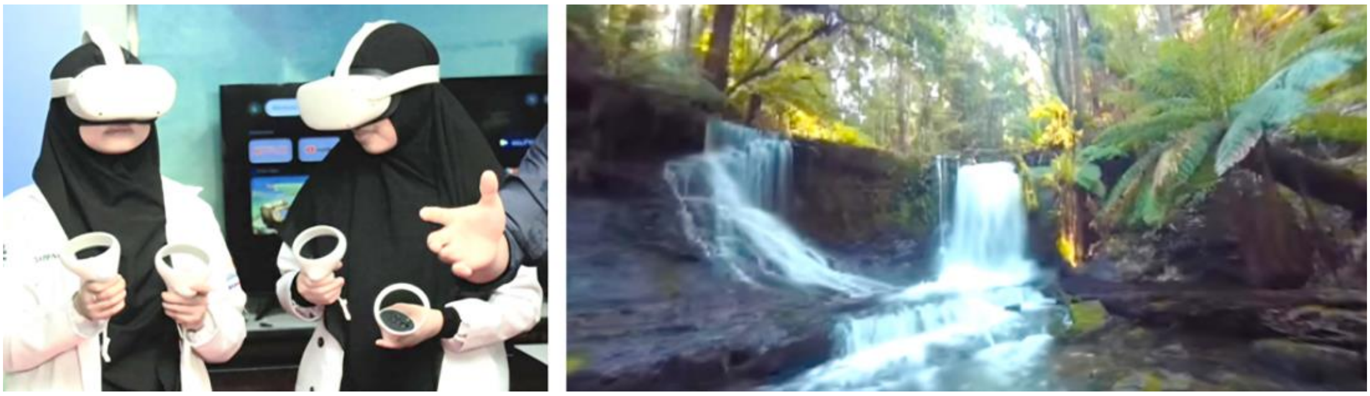

Figure 1. Tools and screen capture of the VR environment (Source: Authors' own elaboration)

particularly important, as these attitudes can significantly influence students' engagement in pro-environmental actions (Levine & Strube, 2012; Meinhold & Malkus, 2005). Traditional educational methods like lectures often fail to engage students effectively, leading educators to explore innovative approaches such as VRT. VR offers immersive learning experiences that can deeply engage students by allowing them to explore ecosystems, witness real-time environmental changes, and experience the moments of human actions firsthand (Ahn et al., 2014). These immersive experiences enhance empathy and emotional engagement, essential for developing positive ENAs (Markowitz et al., 2018).

Research consistently demonstrates the effectiveness of VR in enhancing pro-environmental attitudes. For instance, Shin (2018) found that students engaged in VR-based simulations significantly increased their responsiveness to environmental issues and obligation to PEBs compared to those taught through conventional methods. Similarly, Yuen et al. (2023) revealed that VR experiences, such as virtual visits to endangered ecosystems, strengthen students' ENAs by deepening their emotional connections to the content. Furthermore, the interactivity of VR facilitates the improvement of problem-solving and policymaking skills, as shown by Cheng and Tsai (2019), where students managing virtual ecosystems demonstrated higher motivation and more positive attitudes toward environmental stewardship. However, the impact of VR varies and is influenced by several factors, including VR content, level of immersion, duration of exposure, and students' prior environmental knowledge (ENK) (Xiong et al., 2024). While many studies report significant short-term attitude changes, further investigation is needed to explore the continuing impacts of VR on pro-environmental attitudes and behaviors.

H1. VRT impacts ENA significantly.

ENK fosters awareness and sustainable attitudes (Hungerford & Volk, 1990; Potter, 2009; Zsóka et al., 2013). Traditional methods like lectures often fail to convey complex ecological concepts (Dillon, 2016). VR offers an innovative solution through immersive, experiential learning. VR allows students to experience ecological scenarios that are inaccessible in traditional classrooms. VR-based environments, such as virtual ecosystem tours, significantly enhanced students' understanding of environmental issues (Markowitz et al., 2018). The immersive aspect of VR helps visualize abstract processes like ocean acidification, boosting cognitive engagement and information retention.

Furthermore, VR supports interactive and inclusive learning, catering to diverse learning styles (Chittaro & Zangrando, 2010). Chen (2006) demonstrated that VR simulations of deforestation led to substantial knowledge gains compared to traditional methods. This interactive nature allows students to experiment with ecological dynamics firsthand. Moreover, Tabrizi and Rideout (2017) reported that VR-based education improved students' understanding of sustainability by providing realistic, context-rich experiences. The effectiveness of VR in enhancing knowledge depends on the content's realism, immersion level, and alignment with educational goals (Merchant et al., 2014). While VR shows promise for short-term learning gains, more research is needed on long-term retention (Jensen & Konradsen, 2018).

H2. VRT impacts ENA significantly.

PEB, aimed at reducing individual environmental impact, is a core target of environmental education (Jensen, 2002; Kollmuss & Agyeman, 2002; Kurisu & Kurisu, 2015). Traditional methods often involve passive learning, which does not easily translate into action (Heimlich & Ardoin, 2008). In contrast, VR provides a promising alternative by offering immersive, interactive experiences that foster emotional connections to environmental issues. Participants using VR to explore endangered coral reefs were more likely to support environmental efforts than those informed via traditional media (Ahn et al., 2015, 2016). This reflects VR's ability to evoke empathy, a crucial motivator for PEB (Markowitz et al., 2018). Additionally, VR facilitates experiential learning by allowing students to engage in simulated environmental scenarios, improving their understanding and application of ecological concepts (Cheng & Tsai, 2020; Matovu et al., 2023).

Moreover, VR supports social learning, allowing students to observe and model PEBs and internalize these actions (Bandura, 1977; Yoon et al., 2021). Studies have shown that VR experiences can increase intentions to reduce carbon footprints (Schutte et al., 2017; Schutte & Stilinović, 2017) and enhance engagement with sustainability practices (Tabrizi & Rideout, 2017). However, immersion level, content quality, and experience design significantly impact VR effectiveness (Lee et al., 2020; Zeng et al., 2020). Carefully crafted VR experiences should align with specific educational objectives and engage students emotionally and cognitively (Jensen & Konradsen, 2018). Additional research is necessary to explore the long-term effects of VR on behavior change, as most current studies concentrate on its immediate impacts.

H3. VRT impacts PEB significantly.

Environmental Attitude

ENAs, encompassing individuals' values and beliefs about the environment, play a crucial role in shaping PEBs. According to Ajzen's (2012) theory of planned behavior, attitudes connect ENK with action. The new environmental paradigm (NEP) suggests that heightened ecological awareness fosters responsibility (Dunlap, 2008), while Tarrant and Cordell (1997) found that positive attitudes significantly predict environmentally conscious actions when individuals recognize their impact. Bamberg and Möser (2007) confirms that ENAs, along with social norms and perceived control, strongly influence behavioral intentions, emphasizing the need for supportive conditions to translate attitudes into action (Kaiser & Shimoda, 1999; Kollmuss & Agyeman, 2002).

Further, Schultz et al. (2004) argues that cultural, social, and personal values shape ENAs, advocating for culturally tailored interventions. Stern (2000) stresses the broader social context, suggesting that individual attitude changes alone are insufficient without addressing systemic factors. Similarly, Vining et al. (2002) highlights that structural barriers must be addressed for PEB to flourish. Therefore, while ENAs are pivotal in promoting sustainable behavior, integrating social, cultural, and structural influences is essential to enhance their effectiveness (Ali & Arfandi, 2024; Lewicka, 2011).

H4. ENA impacts ENAs significantly.

Environmental Knowledge

ENK is essential for understanding PEB, as it involves awareness and comprehension of ecological issues, facts, and ecosystem relationships (Fryxell & Lo, 2003). This foundational knowledge supports informed decision-making and encourages sustainable actions (Hines et al., 1987; Kollmuss & Agyeman, 2002). Academic circles have extensively discussed the connection between ENK and PEB. Some studies suggest a significant positive correlation, where increased ENK leads to more pro-environmental actions like purchasing eco-friendly products (Abdeljalil et al., 2022; Bonhi et al., 2024; Copeland & Bhaduri, 2020; Jaiswal et al., 2022; Manucom et al., 2023; Peña et al., 2023; Ventabal et al., 2024). This indicates that knowledge empowers individuals to make informed choices that positively impact the environment (Ali et al., 2021, 2022). However, other studies reveal a weaker or nonexistent link, suggesting that while knowledge is necessary, it is insufficient (Cleveland et al., 2005; Laroche et al., 2002). Factors such as attitudes, values, and situational contexts often play a crucial role in translating knowledge into action (Ajzen, 1991; Dameri & Demartini, 2020).

ENK remains critical in overcoming psychological barriers like fear and misinformation (Kaiser & Gutscher, 2003; Wu & Zhu, 2012). Accurate knowledge is essential for making informed decisions about environmental issues (Kozar & Connell, 2013; Safari et al., 2018; Standing et al., 2008). Tailored educational programs can enhance understanding and foster consistent PEBs (Nisar et al., 2021; Steg & Vlek, 2009). These programs often focus on practical actions that individuals can integrate into their daily routines, promoting sustainable practices (Fenwick, 2007).

H5. ENK impacts PEB significantly.

MATERIAL AND METHOD

Sample and Research Design

This research targeted students who had taken the environmental education class at Universitas Negeri Makassar, involving 336 respondents. The chosen sample size ensured sufficient statistical power to detect VR's significant impact on enhancing students' ENK, attitudes, and PEBs. Researchers collected data through Google Forms-based questionnaires, which efficiently reached respondents and allowed for digital data gathering. A stratified random sampling method was used to reflect the diversity of the student population, dividing them into strata based on their departmental affiliation. Each stratum was proportionally sampled, with students randomly selected from each department according to their representation. This approach ensured balanced representation from all departments, thereby enhancing the generalizability of the research findings to a broader student population (Creswell, 2014; Fraenkel & Wallen, 2009). Participants in this study were required to have completed at least one semester of the environmental education class that integrated VR-based learning. This criterion ensured they had the necessary foundational knowledge and exposure, enhancing the data's accuracy and relevance for the research objectives (Allen & Earl, 2016). **Figure 2** depicts the proposed hypothetical model.

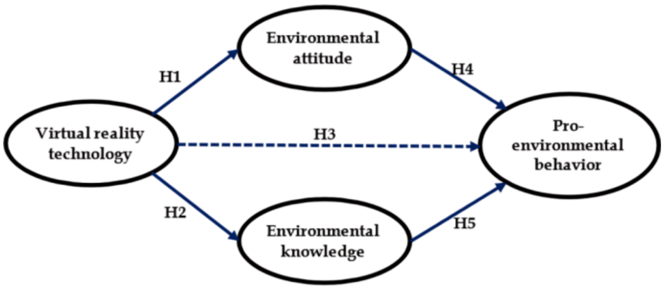

Figure 2. The proposed hypothetical model

Measures and Research Instruments

Virtual reality technology

VR is a powerful educational tool that provides immersive, interactive, and experiential learning environments that enhance students' ability to visualize complex concepts and engage in hands-on activities, leading to improved understanding and retention. In this study, the use of VRT is measured through seven key dimensions: frequency of use, duration of use, level of interactivity, comfort in use, quality of experience, motivation to use VR, and perceived benefits. Each dimension is rated on a 5-point Likert scale, with 1 indicating a low level and 5 indicating a high level. The development of the measurement instrument is based on previous research examining the role of immersive technologies in education (Johnson-Glenberg et al., 2014; Makransky & Lilleholt, 2018; Merchant et al., 2014), aiming to capture the impact of VR on learning outcomes comprehensively.

Environmental knowledge

ENK, a critical factor in fostering PEB, was assessed using the environmental knowledge scale (Kaiser & Fuhrer, 2003), which measures declarative knowledge (basic environmental facts), procedural knowledge (how to perform eco-friendly actions), and effectiveness knowledge (strategies for motivating sustainable behavior). Research indicates that these three types of knowledge significantly enhance PEB (Geiger et al., 2019; Otto & Kaiser, 2014). In this study, participants rated their agreement with knowledge-related statements using a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree), with higher scores reflecting greater environmental understanding. This method comprehensively evaluates knowledge and its role in promoting sustainable actions.

Environmental attitude

ENAs were measured using the NEP scale (Dunlap & Van Liere, 1978). This widely used tool evaluates individuals' beliefs about the relationship between humans and nature. The NEP scale includes statements reflecting ecocentrism (pro-environmental) or anthropocentric views. It assesses attitudes toward crucial issues such as the balance of nature, human environmental impacts, and ecological limits. Participants rate their agreement with each statement on a 5-point Likert scale (1 = "strongly disagree" to 5 = "strongly agree"), with higher scores indicating stronger pro-environmental attitudes. The NEP scale in this study provides a reliable measure of ENAs, offering insights into how these attitudes may influence PEBs (Dunlap et al., 2000; Hawcroft & Milfont, 2010).

Pro-environmental behavior

PEBs were assessed using a self-report section of the questionnaire, where participants indicated the frequency of engaging in various environmentally friendly actions. These behaviors included recycling, conserving energy, reducing waste, and using sustainable modes of transportation like biking or public transit. Respondents rated their participation on a 5-point Likert scale (1 = "never" to 5 = "always") to capture the consistency of their environmental actions. This approach allows for a comprehensive understanding of how frequently individuals practice behaviors that contribute to ecological sustainability, aligning with measures used in studies on PEB (Kollmuss & Agyeman, 2002; Steg & Vlek, 2009).

Reliability of Instruments

The reliability of the four constructs was assessed using Cronbach's alpha coefficient. According to Hair et al. (2013), a Cronbach's alpha value exceeding 0.70 is acceptable for exploratory studies, while a value above 0.80 indicates strong reliability for confirmatory analyses. As presented in **Table 1**, all constructs achieved values above the recommended threshold of 0.70, demonstrating adequate internal consistency (Hair et al., 2013; Taber, 2018). These findings confirm that the constructs are reliably measured, reinforcing the instrument's robustness.

Data Analysis

This study will utilize descriptive statistics and structural equation modeling (SEM) to assess the effect of VR on students' ENK, ENAs, and PEBs. Descriptive analysis will evaluate respondent demographics such as age, gender, faculty, and study year, providing insights into sample characteristics. The study applies covariance-based structural equation modeling using the AMOS program to examine the correlations between variables. This method assesses the direct and indirect effects of VR-based learning on ENK, ENAs, and behavior. Path analysis explores how VR influences knowledge, which then affects attitudes and behavior, offering a clear understanding of the mechanisms linking VR with pro-environmental outcomes. Before testing the structural model, confirmatory factor analysis will be conducted to validate the measurement model,

Table 1. Reliability measures for the measurement model

Constructs	Item	Questions	Cronbach's alpha	Reliability
VRT	VRT1	I regularly use VR for learning.	0.815	0.921
	VRT2	My VR learning experience is interactive.	0.756	
	VRT3	I feel comfortable using VR.	0.808	
	VRT4	VR improves my understanding of the material.	0.892	
ENK	ENK1	I know burning fossil fuels causes global warming.	0.817	0.835
	ENK2	I reduce energy use at home.	0.785	
	ENK3	I aim to decrease plastic waste after learning about its impact.	0.781	
ENA	ENA1	Nature is essential for human survival.	0.744	0.895
	ENA2	Overexploitation of nature threatens our planet.	0.827	
	ENA3	Natural resources are limited; I use them wisely.	0.765	
	ENA4	I align my lifestyle with nature to prevent environmental harm.	0.776	
PEB	PEB1	I actively reduce plastic usage.	0.744	0.886
	PEB2	I turn off unused electronic devices.	0.817	
	PEB3	I limit my use of personal vehicles.	0.800	
	PEB4	I reduce the use of disposable products.	0.770	

Table 2. Demographic characteristics

Characteristic	F	P (%)
Gender		
Male	109	32.44
Female	227	67.56
Age		
< 20 years	179	53.27
21 years	48	14.29
22 years	52	15.48
23 years	45	13.39
24 years	12	3.57
Department		
Elementary school teacher education	87	25.89
Non-formal education	47	13.99
Educational technology	46	13.69
Guidance and counseling	37	11.01
Educational administration	39	11.61
Special education	42	12.50
Early childhood education teacher education	38	11.31
Study year		
1st year	167	49.70
2nd year	65	19.35
3rd year	45	13.39
4th year	35	10.42
> 4th year	24	7.14

Note. F: Frequency; P: Percentage; & n = 336

assessing convergent validity using average variance extracted (AVE) and ensuring discriminant validity for distinctiveness among constructs. Reliability is tested through composite reliability (CR), and hypothesis testing will be performed using path coefficients with a significance threshold ($p < 0.05$).

RESULT

Demographic Characteristics

Demographic characteristics can significantly influence PEBs. This section discusses vital factors such as gender, age, academic department, and study year, which may impact students' ENK, ENAs and actions. Women typically show stronger ENAs than men (Arcury & Christianson, 1993; Xiao & McCright, 2015). Younger students often exhibit higher ecological awareness due to increased educational exposure (Hickman, 2020). Those in environmental science departments are generally more committed to pro-environmental actions than their peers in other fields (Luchs & Mooradian, 2012). Advanced students also tend to have more developed ENAs from specialized coursework (Scannell & Gifford, 2014). Understanding these factors aids in creating targeted ecological interventions.

The study involved 336 participants, comprising 32.44% males and 67.56% females. Most participants were under 20 (53.27%), with other age proportions distributed between 21 and 24 years old. The participants came from various majors, with the most significant number being elementary school teacher education (25.89%), followed by non-formal education (13.99%) and educational technology (13.69%). Based on the year of study, almost half were in their first year (49.70%), while the rest were distributed among the second to more than the fourth year (**Table 2**).

Model Fit Test (Goodness of Fit)

In SEM, achieving an acceptable model fit is critical for validating theoretical models (Byrne, 2016). Model fit refers to how well the hypothesized model corresponds with the observed data. A closer alignment between the model and sample matrix indicates a better fit. Based on the guidelines provided by Boomsma (2000), Hoyle and Panter (1995), and McDonald and Ho (2002), multiple indices were employed to assess the goodness of fit (GOF). These include the Chi-square divided by degrees of freedom (CMIN/df), goodness of fit index (GFI), root mean square error of approximation (RMSEA), comparative fit index (CFI), incremental fit index (IFI),

Table 3. Model goodness of fit summary

Fit indices	Criteria for good fit	Value
CMIN/df	< 2.000	0.968
GFI	> 0.900	0.982
RMSEA	< 0.080	0.007
CFI	> 0.900	0.965
IFI	> 0.900	0.983
NFI	> 0.900	0.954

Table 4. Factor loadings and reliability metrics of constructs

Constructs	Item	Factor loading	CR	AVE
VRT	VRT1	0.783	0.773	0.913
	VRT2	0.795		
	VRY3	0.751		
	VRT4	0.764		
ENK	ENK1	0.805	0.767	0.885
	ENK2	0.756		
	ENK3	0.786		
ENA	ENA1	0.725	0.768	0.910
	ENA2	0.714		
	ENA3	0.759		
	ENA4	0.848		
PEB	PEB1	0.716	0.746	0.898
	PEB2	0.738		
	PEB3	0.805		
	PEB4	0.725		

and normed fit index (NFI). Each index provides different insights into the overall model fit.

The model fit in SEM shows excellent results based on various GOF indices (**Table 3**). The CMIN/df values of 0.968, GFI 0.982, RMSEA 0.007, CFI 0.965, IFI 0.983, and NFI 0.954 all meet or exceed the recommended criteria, indicating a good fit between the hypothesized model and the observed data. Therefore, this model is considered valid and capable of accurately explaining the theoretical relationships in this study.

The measurement model's psychometric properties were assessed for convergent and discriminant validity (Hair et al., 2019; Kline, 2023). Convergent validity was evaluated based on three criteria:

(a) factor loadings greater than 0.70 (Hair et al., 2019),

(b) CR above 0.70 (Bagozzi & Yi, 2012; Fornell & Larcker, 1981), and

(c) AVE exceeding 0.50 (Bagozzi & Yi, 2012; Fornell & Larcker, 1981; Hair et al., 2019).

Table 4 shows that all factor loadings (0.714 to 0.848) are statistically significant and surpass the more stringent threshold of 0.70 (Hair et al., 2019), confirming that each item in the measurement model strongly correlates with its respective construct. Additionally, the CR values (0.773 to 0.768) exceed 0.70, affirming the reliability of the measurement model. The AVE values (0.885 to 0.913) demonstrate that each construct is closely associated with its indicators. Overall, the measurement model displays adequate convergent validity.

Table 5. Hypotheses testing results

Path	β	SE	CR	p	Results
VRT→ENA	0.595	0.013	3.209	0.001**	(**H1**) Accepted
VRT→ENK	0.770	0.019	7.101	0.000***	(**H2**) Accepted
VRT→PEB	0.581	0.014	2.526	0.012*	(**H3**) Accepted
ENA→PEB	0.384	0.026	6.276	0.000***	(**H4**) Accepted
ENK→PEB	0.308	0.012	3.371	0.000***	(**H5**) Accepted

Note. *p < 0.05; **p < 0.01; & ***p < 0.001

Hypotheses Testing

This study tested the hypotheses to assess the effect of VRT on ENAs, ENK, and PEB (PEB). **Table 5** presents the standardized path coefficients (β), standard errors (SE), critical ratios, and p-values for each hypothesis.

The hypothesis testing results in this study indicate that VRT enhances ENAs, knowledge, and behavior. The findings reveal that VRT significantly influences ENA, ENK, and PEB. Specifically, VRT substantially increases participants' ENA ($\beta = 0.595$, $p = 0.001$), improves their ENK ($\beta = 0.770$, $p < 0.001$), and promotes PEB ($\beta = 0.581$, $p = 0.012$). Furthermore, the study confirms the positive relationships between ENA and PEB ($\beta = 0.384$, $p < 0.001$) and ENK and PEB ($\beta = 0.308$, $p < 0.001$), indicating that higher ENAs and knowledge encourage PEB. These results provide empirical support for VRT as an effective tool in environmental education to foster PEB.

DISCUSSION

Research findings indicate that VRT can simultaneously influence ENAs, ENK, and PEB, demonstrating a strong statistical correlation between these three components. The statistical results reinforce the findings of previous studies while offering a more profound understanding through a quantitative approach. This study precisely aligns with Markowitz et al. (2018), which also demonstrated the efficacy of VR simulations in fostering PEB.

The results of this study show that participants exposed to VR simulations depicting environmental degradation exhibited a significant increase in environmental awareness and took tangible actions to mitigate their environmental impact. Participants reported reducing their carbon footprint, a behavior supported by the statistical findings ($\beta = 0.581$, $p = 0.012$). The immersive nature of VR plays a pivotal role in these behavioral changes. By creating vivid and realistic depictions of environmental damage, which are often challenging to visualize daily, VR allows participants to directly experience the adverse effects of human activities on the environment. This immersive experience can trigger empathy and a sense of urgency, motivating participants to engage in pro-environmental actions. Furthermore, Ahn et al. (2014) found that immersive VR experiences increase empathy toward nature, ultimately fostering more environmentally friendly behavior. The empathy generated by the VR experience motivates participants to engage more actively in actions such as recycling and energy conservation. Current research supports this claim by demonstrating that VRT creates profound sensory experiences, enhancing emotional engagement and motivation to act for environmental sustainability.

A significant finding of this study is the notable increase in participants' ENK. VR offers a more interactive and engaging learning platform than conventional methods, allowing participants to understand ecological issues better (Zhang et al., 2020b). This research fortifies that assertion by showing that VRT significantly increases ENK ($\beta = 0.770$, $p < 0.001$). The findings indicate that learning through VRT enables participants to gain a more profound understanding of environmental problems.

This study reveals a significant increase in participants' ENK through VRT. VR offers a more interactive and engaging learning platform than conventional methods, enabling participants to understand ecological issues better (Zhang et al., 2020b). Our research supports this assertion, demonstrating that VRT significantly enhances ENK, with analysis showing a substantial increase ($\beta = 0.770$, $p < 0.001$). By actively engaging participants, VRT allows them to understand better critical ecological concerns such as climate change and biodiversity conservation. These outcomes are reliable with the study of Chen (2016) and Huang et al. (2010), who also identified VR's rich visual and sensory learning experiences as crucial for better grasping environmental problems.

Furthermore, VRT enables participants to receive information and immerse themselves in direct experiences of ecological degradation, reinforcing retention and comprehension. This immersive learning approach aligns with the findings of Slater and Sanchez-Vives (2016), which highlighted VR's effectiveness in teaching biodiversity and conservation efforts. Participants deepen their knowledge and are motivated to take tangible actions to protect the environment. This study underscores the direct correlation between the increased ENK facilitated by VR and subsequent real-world actions to preserve nature.

The enhancement of positive attitudes toward the environment (ENA) is another significant finding of this study. Research by Oh et al. (2021), Schutte and Stilinović (2017), and Yang et al. (2023) supports this result, discovering that VR can create realistic experiences that strengthen positive ENAs. These findings bolster the results of this study, demonstrating that positive ENAs are closely linked with PEB ($\beta = 0.384$, $p < 0.001$). The immersive VR experiences significantly correlate with PEB, indicating that changes in ENAs serve as a crucial catalyst for driving sustainable actions.

The experiences generated by VRT can overcome the psychological distance that often makes environmental issues seem abstract or distant from everyday life (Ahn et al., 2016; Breves & Schramm, 2019). By creating a sense of "presence," where virtual simulations feel real to participants, VRT reduces this psychological distance and enhances the perception of risks associated with environmental issues (Breves & Schramm, 2021). The emotional connection and sense of urgency from these VR experiences motivate participants to act more responsibly and take tangible actions to address environmental problems.

The primary contribution of this research lies in its use of a quantitative approach to deeply analyze the relationship between ENA, ENK, and PEB. This approach strengthens the empirical evidence about the connection between ecological attitudes and knowledge and PEB. It provides a more comprehensive insight into how these variables are statistically interrelated, which previous studies rarely explored. In this study, ENA and ENK were found to have a significant correlation with PEB ($\beta = 0.384$ and $\beta = 0.308$, $p < 0.001$). This indicates that increasing ENAs and enhancing knowledge about environmental issues can drive more environmentally friendly behavior.

Unlike previous studies that often employed qualitative and descriptive methods, the quantitative approach in this research offers more concrete and in-depth measurements. Stern (2000) stated that environmental norms and knowledge have the potential to motivate behavior change, yet they lack supporting statistical data. Similarly, Kollmuss and Agyeman (2002) identified several factors influencing PEB, but their study was more exploratory and did not examine these relationships through statistical correlation.

This study closes significant gaps in previous literature by using advanced statistical analysis to provide a robust empirical foundation for designing effective environmental education policies and programs. Researchers employed a quantitative approach to ensure that the findings are replicable and generalizable, thus enhancing their impact on environmental education and encouraging PEB change. By enriching existing literature, the research guides practical steps to improve environmental awareness and knowledge within the broader community. It demonstrates that VRT effectively enhances attitudes, learning, and PEB. VR's immersive experiences profoundly impact participants, motivating them to adopt environmentally friendly behaviors. This study provides strong empirical evidence on the relationships between ENA, ENK, and PEB, significantly contributing to the development of technology-based learning methods aimed at fostering sustainable behavior change.

Implementing VR into environmental education offers a transformative opportunity to enhance students' ENK, attitudes, and behaviors across educational levels. By allowing students to experience interactive and immersive simulations, VR brings complex environmental issues–such as ecosystem dynamics, climate change impacts, and conservation strategies–into the classroom in visually engaging and experientially impactful ways. This immersive learning approach allows students to understand better and emotionally connect with environmental concepts, fostering ecological literacy and a sense of responsibility from a young age. Early exposure to engaging educational tools may inspire lifelong PEBs, as students gain knowledge and empathy for the natural world.

Successful implementation of VR across educational systems requires coordinated efforts from multiple stakeholders. Collaboration with educational technology developers is essential to design VR content that aligns with curricular goals and pedagogical standards. Government support is also crucial, providing educators with the necessary infrastructure, funding, and training, especially in under-resourced schools. By prioritizing accessibility, teacher training, and resource allocation, institutions can ensure that VR becomes a widely available and effective educational tool. Ultimately, this strategic implementation of VR can cultivate a generation of environmentally conscious and proactive citizens equipped with the knowledge, skills, and motivation to contribute to sustainable development and address pressing global environmental challenges.

CONCLUSION, LIMITATIONS, AND FUTURE RESEARCH

VR has emerged as a highly effective tool in environmental teaching, offering the potential to foster deeper emotional connections with nature than traditional methods. The immersive experiences provided by VR allow users to directly experience real-world ecological challenges, such as deforestation and pollution, which can evoke empathy, concern, and a sense of accountability for the ecosystem. Through simulations of complex and often distant environments, VR can make these issues more concrete and urgent, motivating individuals to adopt PEBs. Moreover, VR enhances environmental awareness and knowledge by making ecological impacts personally relevant, ultimately driving the transformation of knowledge into real-world action.

Maximizing the effectiveness of VR in environmental education requires designing experiences that personalize environmental issues, make abstract concepts tangible, and incorporate emotionally engaging narratives. These strategies increase awareness of ecological problems and strengthen the intent to act. When integrated with traditional educational methods, VR provides a more holistic, interactive experience that enhances cognitive and emotional learning. With advancing technology, VR holds significant potential for promoting sustainable behavioral change, establishing it as a crucial tool in shaping a more environmentally conscious and responsible generation.

Despite the significant findings of this study in demonstrating the potential of VR technology to enhance students' ENK, ENAs, and behaviors, several limitations warrant acknowledgment. A primary limitation is the reliance on self-reported questionnaires collected through an online Google Forms survey, which may introduce social desirability bias; respondents might provide socially acceptable answers rather than entirely accurate ones, potentially compromising the validity of the findings.

Future research on the effectiveness of VR in promoting PEB can explore several vital aspects that have not yet been thoroughly examined. First, upcoming studies could adopt a mixed-methods approach by combining self-report surveys with observational or objective measurements. This approach aims to obtain concrete data on behavioral changes, such as reduced energy consumption and improved waste management practices. By integrating these methods, researchers can comprehensively understand behavioral changes while minimizing the biases inherent in self-reported data.

Next, an important aspect to consider is the influence of VR exposure duration on changes in attitudes and behaviors related to the environment. Although VR experiences have proven effective in enhancing pro-ENK and behavior, the duration of each VR session has not been discussed in detail. Future studies could explore the effects of varying exposure lengths–such as 10 minutes, 30 minutes, and 1 hour–to determine whether longer durations yield a more significant impact. These findings will help researchers identify the optimal duration that maximizes positive ENAs and behaviors changes.

Additionally, future studies should employ a longitudinal approach to understand the long-term effectiveness of VR as an environmental education tool. Measuring changes in PEB over extended periods–such as three months, six months, or even one year after the intervention–will provide deeper insights into the sustainability of VR impact. This approach is essential to ensure that the behavioral changes driven by VR experiences are temporary and persist over the long term.

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