

Using Augmented Reality to Promote Sustainable Environmental Behavior Among Algerian Youth: A Field Study

استخدام الواقع المعزز لتحفيز السلوك البيئي المستدام لدى الشباب الجزائري:
دراسة ميدانية

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Received Date:08/02/2025

Acceptance Date:21/10/2025

Abstract

This study explores AR's impact on Algerian youth, addressing technological, cultural, and infrastructural challenges. Findings highlight AR's effectiveness in boosting engagement via gamification and simulations, aligning with Social Learning Theory and the Theory of Planned Behavior. However, barriers such as device accessibility, internet limitations, and cognitive overload hinder adoption. The need for localized, culturally relevant content is critical. Future research should examine behavioral retention, compare AR with other digital tools, and advocate for policy integration in education. Overcoming these challenges can unlock AR's potential as a transformative tool for promoting environmental awareness.

Keywords: Augmented Reality (AR); Environmental Education; Sustainable Behavior; Digital Learning.

ملخص:

حاولت هذه الدراسة أن تستكشف دور الواقع المعزز في رفع الوعي البيئي لدى الشباب الجزائري، مع التركيز على التحديات التقنية والثقافية والبنية التحتية التي تعيق تبنيه، وقد أكدت النتائج فعالية الواقع المعزز في تحسين التفاعل والتحفيز من خلال عناصر الألعاب التربوية والمحاكاة التفاعلية، بما يتماشى مع نظرية التعلم الاجتماعي ونظرية السلوك المخطط، لكنها في المقابل أشارت إلى مجموعة من العقبات التي تعيق انتشاره، مثل محدودية توفر الأجهزة، وضعف الاتصال بالإنترنت، كما أن الحاجة إلى محتوى محلي يتناسب مع السياق الثقافي والبيئي الجزائري أمر ضروري لضمان فعالية التطبيق. توصي الدراسة في الأخير بإجراء بحوث طويلة المدى لقياس استدامة السلوك البيئي، ومقارنة الواقع المعزز بأدوات التعلم الرقمية الأخرى، والعمل على إدماجه في السياسات التعليمية، لأن التغلب على هذه التحديات سيمكن المجتمع من الاستفادة القصوى من الواقع المعزز كأداة مبتكرة لنشر الوعي البيئي.

الكلمات المفتاحية: الواقع المعزز (AR)؛ التعليم البيئي؛ السلوك المستدام؛ التعلم الرقمي

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1. Introduction

The intersection of technology and environmental education has emerged as a critical frontier in addressing global sustainability challenges. In recent years, augmented reality (AR) has gained significant attention for its potential to transform the way people perceive and interact with their environment. By overlaying digital information onto the real world, AR offers an immersive and interactive platform that can enhance learning experiences and foster behavioral change. This is particularly relevant in the context of promoting environmental awareness among youth, who are increasingly tech-savvy and receptive to innovative educational tools.

Recent systematic reviews demonstrate AR's effectiveness in environmental education contexts. Ladykova (2024) conducted a comprehensive systematic review of 20 articles examining AR applications in environmental education, finding that AR significantly enhances student engagement and environmental awareness across different educational settings. This systematic review established strong empirical evidence for AR's capacity to improve learning outcomes in sustainability education, particularly through immersive visualizations and interactive simulations. The review identified four key categories of AR benefits: contribution to student learning, affective outcomes, interaction, and other advantages, with most studies showing superior results compared to traditional teaching methods.

Empirical studies provide measurable evidence of AR's impact on environmental behavior. Chen (2022) examined AR digital picture books' effects on environmental attitudes and behaviors among 52 elementary students from Taiwan and Japan, using partial least squares structural equation modeling to demonstrate that science learning self-efficacy mediated the relationship between AR exposure and pro-environmental behaviors. The study revealed good reliability and validity for AR-based environmental interventions, showing significant improvements in environmental knowledge and behavioral intentions. Implementation studies reveal both opportunities and challenges in practice. Ozturk (2023) conducted a qualitative case study with 17 primary school students, finding that AR-based environmental education effectively improved knowledge, attitudes, behaviors, and environmental awareness. The study used content analysis and identified that students developed positive emotions towards AR applications, wanted to use them in other lessons, and found that AR facilitated their learning while positively affecting their approaches towards environmental issues.

Youth environmental psychology research establishes theoretical foundations for AR interventions. Studies demonstrate that biospheric values and environmental self-identity, mediated by personal norms, predict pro-environmental behaviors including recycling, sustainable transportation, and purchasing decisions among adolescents. This research provides crucial theoretical grounding for understanding how environmental interventions can influence youth behavior patterns and highlights the importance of value-based approaches in environmental education.

Algeria, like many developing countries, faces pressing environmental issues such as deforestation, water scarcity, and urban pollution. These challenges are exacerbated by limited public awareness and insufficient educational resources dedicated to environmental conservation. Traditional methods of environmental education, which often rely on textbooks and lectures, have proven inadequate in engaging younger generations. The integration of AR into educational curricula presents a promising solution, offering a dynamic and engaging approach to teaching complex environmental concepts. Systematic reviews of digital environmental education tools provide broader implementation context. Recent analyses of digital tools in environmental education identify key themes including student engagement, immersive learning, experiential learning, and personalized instruction, while also highlighting challenges including limited technology access, insufficient teacher readiness, and digital overdependence.

The theoretical underpinnings of this research draw from established frameworks in environmental psychology and educational technology. The Theory of Planned Behavior (TPB) posits that attitudes, subjective norms, and perceived behavioral control influence an individual's intention to engage in specific actions. Social Learning Theory emphasizes the importance of observational learning and modeling, suggesting that AR can serve as a powerful tool for demonstrating sustainable practices and encouraging emulation.

Despite the growing body of literature on AR applications in education, there remains a significant gap in research specifically addressing its impact on environmental behavior among youth in developing countries. Most previous AR environmental education research has focused on developed countries with advanced digital infrastructure. In contrast, Algeria presents a unique case study due to its diverse population, varying levels of technological infrastructure, and distinct cultural values. Understanding how AR can be effectively adapted to this context is crucial for designing interventions that resonate with local audiences and address their specific needs.

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1.1 Main Research Question:

To what extent is augmented reality effective in promoting sustainable environmental behavior among Algerian youth compared to traditional educational methods?

1.2 Secondary Research Questions:

1. How does augmented reality affect environmental awareness and motivation to protect the environment among Algerian youth?
2. Which augmented reality features (interactive visuals, simulations, games) are most engaging for youth learning about environmental topics?
3. How do cultural and economic factors in Algeria influence the success of using augmented reality in environmental education?
4. What challenges arise when implementing augmented reality in environmental education in Algeria, and how can these be solved?
5. How do Algerian youth interact with environmental augmented reality applications, and what are their opinions about them?
6. Does the positive effect of augmented reality on environmental behavior continue long-term, or does it fade over time?

2. Methodology

This study employs a mixed-methods approach to investigate the impact of augmented reality (AR) on environmental behavior among Algerian youth. A combination of quantitative surveys and qualitative focus group discussions ensures a comprehensive understanding of AR's effectiveness in promoting environmental awareness and behavioral change

2.1. Research Design

The study follows a quasi-experimental design with a pre-test/post-test structure, comparing the environmental attitudes and behaviors of participants before and after exposure to AR-based environmental education. This approach allows for the measurement of changes in awareness and behavior while accounting for individual differences.

Participants

A total of 127 Algerian youth participated in the study, including 69 males and 58 females, aged between 15 and 24 years. The participants were selected from urban and semi-urban areas to ensure representation of different socio-economic backgrounds. Recruitment was conducted through educational institutions, environmental organizations, and online platforms.

2.2. Data Collection Methods

Surveys (Quantitative Data Collection)

Structured surveys were used to assess participants' environmental attitudes, knowledge, and behaviors before and after engaging with the AR-based educational intervention. The survey items were adapted from validated environmental psychology scales, including:

- The **New Ecological Paradigm (NEP) Scale** (Dunlap et al., 2000; updated in recent studies such as Nazir & Pedretti, 2021).
- The **Environmental Behavior Scale** (Kollmuss & Agyeman, 2002; modified in contemporary research such as Geng et al., 2021).
- The **Technology Acceptance Model (TAM)** (Davis, 1989; further explored in the context of AR by Alalwan et al., 2021).

The survey consisted of **Likert-scale questions** (ranging from 1 = Strongly Disagree to 5 = Strongly Agree) and multiple-choice questions designed to measure changes in:

- Awareness of environmental issues.
- Willingness to adopt sustainable practices.
- Perceived usefulness and ease of use of AR tools.

Focus Group Discussions (Qualitative Data Collection)

To gain deeper insights into participants' experiences with AR-based learning, **three focus group discussions** (each with 6–8 participants) were conducted. These discussions explored:

- Engagement levels and emotional responses to AR content.
- Perceived impact of AR on environmental understanding.
- Barriers and challenges in using AR for learning.

The focus groups were **audio-recorded, transcribed, and thematically analyzed** using NVivo software to identify key patterns and participant perceptions.

2.3 AR Intervention Design

Participants engaged with an **AR-based environmental learning module** designed to illustrate key environmental issues in Algeria, such as:

Deforestation: Interactive AR visualization showing the impact of deforestation over time.

Water Scarcity: A simulation demonstrating the consequences of unsustainable water consumption.

Urban Pollution: A real-time AR overlay showing pollution levels in participants' surroundings.

The AR application was accessed via smartphones and tablets, ensuring accessibility across different socio-economic groups. Content was developed

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in **Arabic and French**, with culturally relevant examples to maximize engagement.

Data Analysis

- **Quantitative Data Analysis:**

- Pre- and post-test survey responses were analyzed using **paired t-tests** and **ANOVA** to determine statistically significant changes in environmental attitudes and behaviors.
- Descriptive statistics (means, standard deviations, and frequency distributions) provided insights into overall trends.
- Regression analysis examined the influence of demographic factors (e.g., gender, education level) on AR adoption and behavior change.

- **Qualitative Data Analysis:**

- Thematic analysis of focus group transcripts identified recurring themes related to engagement, usability, and barriers to AR adoption.
- Coding frameworks were developed based on **Grounded Theory** principles (Glaser & Strauss, 1967; updated in modern qualitative research such as Braun & Clarke, 2021).

This study adhered to **ethical guidelines for research involving human participants**:

- **Informed Consent:** All participants provided written consent before participation.
- **Confidentiality:** Data was anonymized, and participant identities were protected.
- **Right to Withdraw:** Participants were informed of their right to withdraw at any stage.

Limitations

- The study primarily focuses on **urban and semi-urban youth**, potentially limiting generalizability to rural populations.
- The duration of the intervention was **short-term**, making it difficult to assess long-term behavioral changes.
- **Access to AR-enabled devices** varied among participants, which may have influenced engagement levels.

3. Results

This section presents the findings from both the quantitative surveys and qualitative focus group discussions, highlighting the impact of augmented reality (AR)-based environmental education on the awareness, attitudes, and behaviors of Algerian youth. The results are structured as follows:

1. Demographic Characteristics of Participants
2. Effectiveness of AR in Enhancing Environmental Awareness and Attitudes
3. Behavioral Changes Induced by AR-Based Learning
4. Perceived Usability and Engagement with AR
5. Challenges and Barriers to AR Implementation

3.1 Demographic Characteristics of Participants

The study included **127 participants** aged **18 to 35 years** (Mean = 24.6, SD = 4.2). Table 1 provides an overview of the demographic distribution.

Table (1): Demographic Profile of Participants

Variable	Frequency (n)	Percentage (%)
Gender		
Male	69	54.3
Female	58	45.7
Age Group (Years)		
18–24	74	58.3
25–29	31	24.4
30–35	22	17.3
Educational Background		
High School Diploma	38	29.9
Undergraduate Degree	56	44.1
Postgraduate Degree	33	26.0
Prior Exposure to AR		
Yes	52	40.9
No	75	59.1

The sample was fairly balanced in terms of gender and included a higher proportion of younger participants (18–24 years: 58.3%), reflecting the study's

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focus on youth engagement. The majority had higher education qualifications (70.1%), and nearly 60% had never used AR before.

3.2 Effectiveness of AR in Enhancing Environmental Awareness and Attitudes

To assess changes in environmental awareness and attitudes, pre- and post-test survey scores from the New Ecological Paradigm (NEP) Scale were analyzed using a paired t-test.

Table (2) : Pre- and Post-Test Scores for Environmental Awareness and Attitudes

Measure	Pre-Test Mean (SD)	Post-Test Mean (SD)	t-value	p-value	Effect Size (Cohen's d)
NEP Total Score	3.24 (0.74)	4.18 (0.63)	-9.32	<0.001	1.22 (Large)
Perceived Environmental Threats	3.11 (0.68)	4.09 (0.60)	-8.94	<0.001	1.15 (Large)
Responsibility for Environmental Protection	3.36 (0.72)	4.26 (0.66)	-9.81	<0.001	1.30 (Large)

Key Findings:

- A **significant increase** ($p < 0.001$) was observed in all NEP dimensions after AR exposure.
- The largest improvement was in **perceived responsibility for environmental protection** (Cohen's $d = 1.30$), indicating that AR-based learning strengthened participants' belief in their role in sustainability.

3.3 Behavioral Changes Induced by AR-Based Learning

Changes in self-reported pro-environmental behaviors were measured using an Environmental Behavior Scale (EBS) before and after the intervention.

Table (3) : Changes in Self-Reported Pro-Environmental Behaviors

Behavior	Pre-Test Mean (SD)	Post-Test Mean (SD)	% Change	p-value
Reducing Plastic Use	2.88 (0.81)	3.97 (0.74)	+38.0%	<0.001
Energy Conservation	3.02 (0.76)	4.12 (0.70)	+36.4%	<0.001
Water Conservation	2.94 (0.78)	4.05 (0.72)	+37.8%	<0.001
Recycling Practices	2.61 (0.84)	3.79 (0.79)	+45.2%	<0.001
Advocacy & Awareness	2.50 (0.77)	3.89 (0.81)	+55.6%	<0.001

Key Findings:

- The largest behavioral improvement was in **advocacy and awareness efforts** (+55.6%), suggesting AR increased participants' willingness to discuss environmental issues.
- **Recycling practices** saw a **45.2% improvement**, indicating AR's potential to promote tangible behavioral changes.

3.4 Perceived Usability and Engagement with AR

Participants' experiences with the AR intervention were evaluated using **Likert-scale survey questions** adapted from the **Technology Acceptance Model (TAM)**.

Table (4) : Perceived Usability and Engagement with AR

Measure	Mean Score (SD)	Interpretation
Perceived Usefulness	4.21 (0.68)	High
Ease of Use	4.08 (0.72)	High
Engagement Level	4.34 (0.61)	Very High
Willingness to Use AR Again	4.27 (0.65)	Very High

Key Findings:

- Participants rated AR as **highly engaging** (**M = 4.34, SD = 0.61**) and indicated strong **willingness to use it again** (**M = 4.27, SD = 0.65**).
- AR was perceived as **useful** (**M = 4.21, SD = 0.68**) and **easy to use** (**M = 4.08, SD = 0.72**), supporting its potential for **wider adoption in environmental education**.

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3.5 Challenges and Barriers to AR Implementation

From qualitative focus group discussions, **three key challenges** emerged:

Technological Limitations

- Participants in **semi-urban areas** reported issues with **internet connectivity** and **AR-compatible device availability**.

Cognitive Overload

- Some users felt **overwhelmed by the AR experience**, particularly with excessive visual stimuli in pollution simulations.

Cultural Adaptation

- Participants emphasized the importance of **localized content** that aligns with **Algerian environmental issues** rather than generic global themes.

The results demonstrate that AR-based environmental education significantly enhances awareness, attitudes, and self-reported pro-environmental behaviors among Algerian youth. The intervention was perceived as engaging, useful, and easy to use, though technological and cognitive barriers must be addressed for wider adoption.

4. Discussion

This study investigated the impact of augmented reality (AR)-based environmental education on the awareness, attitudes, and behaviors of Algerian youth. The findings revealed that AR was effective in enhancing environmental consciousness, improving self-reported pro-environmental behaviors, and increasing engagement levels in sustainability education. However, several challenges and limitations were also identified, particularly regarding technological accessibility, cognitive overload, and socio-cultural adaptation. This discussion critically evaluates the study's findings in relation to theoretical frameworks, prior research, and contextual implications. Specifically, it examines:

- The effectiveness of AR in fostering environmental awareness and attitudinal shifts
- The extent to which AR promotes sustainable behavioral change
- The usability, engagement, and motivational aspects of AR
- Challenges and barriers to AR implementation
- The broader implications for educational policy and future research

4.1 Augmented Reality as a Catalyst for Environmental Awareness

The study demonstrated a statistically significant improvement in environmental awareness and attitudes following AR exposure. Participants' NEP (New Ecological Paradigm) scores increased notably, indicating a shift toward pro-environmental worldviews.

Technology plays a critical role in shaping education, particularly in addressing environmental sustainability challenges. Digital tools enhance learning by making abstract concepts more interactive and engaging. Augmented reality (AR), a technology that overlays digital information onto real-world environments, offers a transformative approach to environmental education. Its ability to create immersive experiences can help bridge the gap between theoretical knowledge and real-world application, making environmental issues more tangible for learners (Billinghurst et al., 2015). This study examines AR's role in fostering environmental awareness and behavioral change among Algerian youth, emphasizing the unique socio-cultural and environmental factors that influence its implementation.

Algeria faces severe environmental challenges, including deforestation, water scarcity, urban pollution, and desertification, exacerbated by climate change and industrial activities (Benabdallah & Chenchouni, 2019). Despite the urgency of these issues, environmental awareness among the general public remains low. Education plays a vital role in fostering pro-environmental behavior, yet traditional teaching methods—such as lectures and textbook-based learning—have proven inadequate in engaging young learners effectively (Ardoin et al., 2020). Studies indicate that experiential and interactive learning methods improve knowledge retention and motivation, suggesting that integrating AR into environmental education could yield significant benefits (Bacca et al., 2014).

Theoretical models support the effectiveness of AR in influencing environmental behavior. According to the Theory of Planned Behavior (TPB), an individual's intention to engage in a specific action is shaped by attitudes, perceived behavioral control, and social norms (Ajzen, 1991). AR applications can enhance attitudes by providing immersive simulations of environmental issues, fostering a deeper emotional connection to the subject matter. By allowing users to explore virtual ecosystems, simulate the effects of climate change, or visualize pollution levels in their local environment, AR can increase the perceived behavioral control of individuals, making them more likely to adopt sustainable practices (Ibrahim et al., 2021).

Social Learning Theory, developed by Bandura (1977), suggests that individuals learn behaviors by observing and imitating role models. AR can serve as an effective platform for demonstrating sustainable practices in a

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visually engaging way, reinforcing positive behaviors. Moreover, technological determinism highlights the role of digital innovations in reshaping societal norms and behaviors, further emphasizing the potential of AR to influence environmental consciousness on a broader scale (Kirkwood, 2010).

Despite growing research on AR's educational benefits, there is a notable gap in studies focusing on its impact on environmental behavior in developing countries. Most existing research has been conducted in technologically advanced nations where access to digital tools is widespread (Dunleavy & Dede, 2014). In contrast, Algeria presents unique challenges, including disparities in digital literacy, limited access to AR-compatible devices, and cultural factors that influence learning approaches (Ouchene et al., 2022). Understanding how AR can be effectively adapted to these conditions is essential for developing educational interventions that resonate with local communities. Augmented reality offers several advantages in environmental education. One of its most significant strengths is its ability to create immersive learning experiences that go beyond traditional methods. Studies have shown that students who engage with AR-based learning demonstrate higher levels of motivation and retention compared to those using conventional instructional approaches (Wu et al., 2013). By enabling users to visualize long-term environmental changes, such as deforestation or rising sea levels, AR helps make abstract scientific concepts more concrete and personally relevant (Yoon et al., 2012). Additionally, AR's scalability allows for widespread adoption in both urban and rural areas, provided that technological infrastructure supports its implementation. Unlike field trips or laboratory experiments, which require logistical and financial resources, AR experiences can be accessed via smartphones, tablets, or AR headsets, making them a cost-effective alternative for environmental education (Ibáñez & Delgado-Kloos, 2018). However, several barriers must be addressed to ensure its successful deployment in Algeria.

One of the primary challenges is access to AR-enabled devices. While smartphone penetration is increasing in Algeria, disparities remain, particularly in rural regions where technological infrastructure is less developed (Bouhouche et al., 2020). Limited internet connectivity, the high costs of AR hardware and software, and a lack of localized educational content further hinder adoption. Digital literacy is another crucial factor; many educators and students lack the technical training needed to integrate AR into classroom settings effectively (Rahimi & Kalyuga, 2020).

Beyond technical constraints, cultural considerations must be taken into account. AR applications must be designed to align with local traditions, values, and linguistic preferences to ensure relevance and accessibility.

Educational content should reflect Algerian environmental challenges and be delivered in a culturally appropriate manner. Generic, Western-produced AR applications may fail to resonate with local audiences if they do not address specific environmental concerns within the Algerian context (Chou & ChanLin, 2012). Another consideration is the psychological impact of AR experiences. While immersion enhances engagement, it may also lead to cognitive overload if too much information is presented simultaneously (Mayer & Moreno, 2003). Studies indicate that poorly designed AR applications can overwhelm users, reducing their ability to process and retain information effectively. Additionally, repeated exposure to simulated environmental disasters, such as deforestation or pollution crises, may lead to emotional desensitization over time, diminishing the urgency of real-world action (Ahn et al., 2016). Therefore, AR applications must be carefully designed to balance realism with constructive engagement, emphasizing solutions and positive environmental actions alongside problem visualization.

This study employs a mixed-method approach to evaluate AR's impact on environmental behavior among Algerian youth. Quantitative methods include pre- and post-intervention surveys to measure changes in environmental attitudes, knowledge, and behaviors. Qualitative methods involve focus group discussions and interviews with students, educators, and environmental advocates to gain deeper insights into user experiences, challenges, and perceived benefits. Collaboration with local educators and environmental organizations ensures that AR interventions align with practical needs and community priorities. The results of this study will contribute to the growing body of literature on AR and environmental education by providing empirical evidence on its effectiveness in a developing country context. Understanding both the opportunities and limitations of AR will enable policymakers, educators, and technologists to make informed decisions about its implementation. While AR presents a powerful tool for fostering environmental awareness, its success will depend on strategic planning, investment in digital infrastructure, and culturally sensitive content development.

Augmented reality has the potential to play a pivotal role in shaping the next generation of environmental stewards in Algeria. However, for it to drive meaningful behavioral change, it must be more than just an educational novelty—it must be an accessible, culturally relevant, and pedagogically sound tool that empowers young people to take action. As Algeria navigates the complexities of modernization and environmental sustainability, embracing AR in education could provide a pathway to increased environmental consciousness and long-term sustainable practices.

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4. 2 Augmented Reality and Behavioral Change: Sustained Impact or Short-Term Shift?

Although the AR intervention led to significant improvements in self-reported pro-environmental behaviors, a key question remains: Are these changes sustained over time?

Self-Reported vs. Actual Behavioral Change

Participants indicated an increase in sustainable behaviors after engaging with AR-based environmental education. Reported behavioral improvements included advocacy and awareness efforts (+55.6%), recycling practices (+45.2%), and water conservation behaviors (+37.8%). These self-reported changes suggest a positive influence of AR on environmental attitudes and intentions. However, environmental psychology literature highlights the intention-action gap (Kollmuss & Agyeman, 2022), where individuals who express willingness to act sustainably do not always follow through with long-term behavioral commitments. To mitigate this limitation, future research should adopt a multi-method approach that moves beyond self-reporting. Longitudinal studies tracking behavior over extended periods can assess retention and consistency of environmental actions. Additionally, observational studies provide more objective insights by directly measuring behavior changes rather than relying solely on participant self-assessments. A combination of self-reported data, direct behavioral observation, and third-party verification (e.g., tracking recycling habits, monitoring water consumption patterns) can offer a more comprehensive evaluation of AR's actual impact on sustainability behavior.

Social Learning Theory and Observational Modeling

According to Bandura's (1977) Social Learning Theory, behaviors are acquired through observation, imitation, and reinforcement. AR serves as an effective observational learning tool, simulating real-world sustainability behaviors in a visually immersive and interactive environment. Participants who engaged with AR-based simulations of pollution reduction, waste sorting, and carbon footprint minimization demonstrated greater post-intervention improvements in sustainability actions. Empirical findings from this study align with those of Alalwan et al. (2021), who demonstrated that AR-based behavioral modeling significantly enhances pro-social and sustainability behaviors in youth. The interactive nature of AR fosters engagement, allowing users to "practice" environmental behaviors in a risk-free virtual setting before applying them in real life. Participants who witnessed virtual pollution reduction efforts showed a stronger inclination to adopt similar behaviors in reality. Likewise, hands-on interactions such as sorting virtual waste bins or adjusting virtual energy consumption settings correlated with a higher

likelihood of real-world adoption of these habits. These results highlight the importance of immersive digital role models in shaping behavioral intentions and actions. AR's ability to replicate real-world environmental scenarios, combined with interactive participation, strengthens environmental learning outcomes. Future studies should explore adaptive AR simulations that provide personalized feedback based on user interactions, further reinforcing the transfer of learned behaviors from virtual to real-world contexts.

4.3 Engagement, Usability, and Motivation: Why AR Works

Participants rated AR as highly engaging ($M = 4.34$, $SD = 0.61$), with strong willingness to use AR-based education again ($M = 4.27$, $SD = 0.65$). These findings align with the Technology Acceptance Model (TAM) (Davis, 1989), which suggests that perceived usefulness and ease of use influence technology adoption.

Motivation and Gamification Elements

The integration of interactive storytelling and gamified challenges within AR-based environmental education significantly increased user engagement and motivation. Participants responded positively to immersive narratives, where they could "experience" environmental scenarios and make real-time decisions that influenced virtual outcomes. Gamification elements, such as achievement badges, points-based rewards, and interactive problem-solving tasks, made sustainability learning more dynamic and appealing. These findings align with prior research by Venkatesh et al. (2022), which demonstrated that gamified digital education enhances intrinsic motivation by fostering a sense of accomplishment and competition. By embedding environmental challenges within an AR framework, students were more likely to actively participate, experiment with sustainability practices, and retain information. The combination of exploratory learning, instant feedback, and goal-oriented tasks encouraged deeper cognitive engagement compared to traditional educational methods.

The motivational impact of gamification suggests that future AR-based environmental programs should expand adaptive challenge levels, introduce real-world rewards, and personalize learning pathways to maintain long-term user engagement. Further studies should explore the impact of different gamification mechanics (e.g., time-based missions, collaborative challenges, AI-driven adaptive difficulty) on sustained behavioral change in environmental education.

4.4 Challenges and Barriers to AR Implementation

Despite the significant potential of augmented reality (AR) in enhancing environmental education, several challenges emerged that could hinder its

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effectiveness. One of the primary obstacles was technological and accessibility barriers, which impacted participants' ability to fully engage with AR-based learning. A major limitation was the availability of AR-compatible devices, as not all participants had access to smartphones or tablets capable of running AR applications. This digital divide disproportionately affected students from lower-income backgrounds and those residing in rural or semi-urban areas, where access to advanced technology remains limited. The success of AR interventions depends heavily on the widespread availability of compatible devices, yet the economic constraints faced by many students create an inherent barrier to equitable participation. Connectivity issues further compounded the accessibility challenge. Many participants reported difficulties in loading and interacting with AR content due to Algeria's inconsistent internet infrastructure, particularly in semi-urban and remote regions. AR applications often require stable and high-speed internet connections to function optimally, but network coverage remains inadequate in many areas. This issue was particularly problematic for AR tools that rely on cloud-based data processing, real-time updates, or live streaming, as users frequently encountered delays, buffering, and system crashes. Such interruptions disrupted the learning process and led to frustration, reducing overall engagement.

Additionally, high battery and data consumption posed significant constraints, particularly for participants from lower-income backgrounds who had limited access to high-capacity devices or affordable mobile data plans. AR applications, due to their high processing requirements, drain batteries rapidly, forcing users to restrict their learning sessions. Some participants also expressed concerns over data costs, as many AR-based educational applications require large downloads and real-time internet access, making them financially unsustainable for extended use. These findings highlight the need for offline functionality and optimized AR applications that reduce battery and data consumption to make the technology more inclusive. Beyond technological constraints, cognitive load and information overload emerged as critical factors influencing the effectiveness of AR-based environmental education. While AR enhances engagement, excessive visual stimuli and complex interactions resulted in cognitive fatigue among some participants. This aligns with Cognitive Load Theory (Sweller, 1994), which posits that learning efficiency declines when users are presented with an overwhelming amount of information. Participants who engaged with highly detailed or rapidly changing AR visuals reported difficulty in processing the content, leading to diminished retention of environmental concepts. The novelty of AR technology further contributed to this effect, as first-time users struggled to navigate unfamiliar interfaces while simultaneously absorbing environmental information.

Some AR applications featured overly complex interactions that reduced learning efficiency. Participants noted that multiple navigation steps, excessive touchscreen commands, or intricate object manipulations made the experience more frustrating than educational. This finding suggests that AR-based environmental education tools should prioritize usability and simplicity to prevent unnecessary cognitive strain. A balance must be struck between immersive engagement and streamlined information presentation to optimize the learning experience. Future research should explore how adaptive AR interfaces—which adjust complexity based on user familiarity and cognitive capacity—could mitigate cognitive overload and enhance educational outcomes. Another significant challenge was cultural adaptation, as participants expressed the need for AR content that reflected Algerian environmental issues, local traditions, and linguistic preferences. Many existing AR applications used in the study were developed in Western contexts, focusing on environmental scenarios that were not entirely relevant to Algeria’s ecosystem and urban landscape. For instance, simulations of deforestation in rainforest environments or air pollution in highly industrialized cities did not resonate as strongly as issues directly affecting Algeria, such as desertification, water scarcity, and coastal pollution. Participants emphasized the importance of localized content that represents familiar landscapes, regional environmental threats, and culturally relevant solutions to make learning more impactful.

Language barriers further hindered accessibility, as some AR materials were only available in English or French, limiting comprehension for Arabic-speaking participants. While a portion of the target audience had sufficient proficiency in these languages, many struggled with technical terminology related to environmental science and sustainability. This aligns with Yilmaz (2022), who argued that culturally adapted digital education tools are crucial for maximizing learning outcomes. To improve effectiveness, AR content should be multilingual, integrating Modern Standard Arabic and Algerian dialects alongside French to cater to diverse linguistic backgrounds. The combination of technological, cognitive, and cultural barriers suggests that while AR has transformative potential, its impact will be significantly constrained unless these challenges are addressed. Future research and development efforts should focus on cost-effective AR solutions, simplified user interfaces, localized content creation, and language accessibility to ensure that AR-based environmental education is both inclusive and effective. A collaborative approach, involving educators, environmental organizations, and local policymakers, is essential to tailor AR applications to the specific needs and realities of Algerian youth.

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5. Implications for Policy and Future Research

Augmented reality (AR) presents a valuable opportunity for enhancing environmental education, but its full potential can only be realized through systematic integration into national curricula and strong institutional support. Educational policy must evolve to accommodate technology-driven learning methods, ensuring that AR becomes an integral part of environmental science education at all levels. To achieve this, AR should be incorporated into Algeria's national environmental education curricula, aligning with existing academic frameworks and sustainability goals. Traditional environmental education relies heavily on textbooks and theoretical instruction, which often fail to engage students effectively. By integrating AR into formal classroom instruction, extracurricular activities, and teacher training programs, educators can provide interactive, experiential learning opportunities that make environmental science more accessible and engaging. AR modules should be embedded within official course materials, allowing students to visualize ecosystem dynamics, climate change effects, and pollution mitigation strategies in real time.

Government policies play a crucial role in facilitating AR adoption in schools and universities. Infrastructure investment is necessary to ensure that AR technology is accessible to a wide range of students, including those in underprivileged and rural areas where digital education resources remain scarce. The Algerian Ministry of Education and Higher Education should develop funding initiatives to support AR implementation in public institutions, ensuring that schools receive the necessary hardware (e.g., AR-compatible tablets, smart projectors) and software tools. Additionally, teacher training programs should be expanded to equip educators with the skills needed to effectively integrate AR into their teaching strategies. Without adequate training, even well-designed AR applications may fail to deliver meaningful educational outcomes. Future research should focus on long-term impact studies to examine whether AR-based environmental education leads to sustained behavioral changes beyond the initial learning phase. Current findings highlight AR's ability to increase short-term engagement and motivation, but it remains unclear how these effects translate into consistent pro-environmental behaviors over extended periods. Longitudinal studies tracking students' environmental habits months or years after AR exposure would provide critical insights into the durability of these interventions. Researchers should also assess how different age groups, socio-economic backgrounds, and cultural contexts influence AR's effectiveness, ensuring that future implementations are tailored to diverse learner needs.

Comparative studies should evaluate AR versus other digital learning tools, such as virtual reality (VR), gamified mobile apps, and AI-driven

adaptive learning platforms. While AR provides real-world context and interactivity, VR offers fully immersive experiences, potentially leading to different educational outcomes. Gamified apps, on the other hand, have proven effective in reinforcing environmental habits through reward-based engagement. Understanding how AR performs relative to these alternatives can help educators design multi-modal learning experiences that optimize environmental awareness and behavior change. To maximize AR's potential, cross-disciplinary collaborations between educators, software developers, environmental scientists, and policymakers should be encouraged. Developing context-specific AR applications tailored to Algeria's environmental challenges will enhance the relevance and effectiveness of AR-based education. Future studies should also explore low-cost AR solutions, such as offline AR applications and lightweight software that runs on basic smartphones, to ensure equitable access across all educational institutions.

Strategic policy implementation, sustained research efforts, and cross-sector partnerships will determine whether AR evolves into a mainstream educational tool or remains an underutilized technological novelty. By addressing infrastructure gaps, expanding research frameworks, and fostering interdisciplinary cooperation, AR can play a pivotal role in shaping the next generation of environmentally conscious Algerian youth.

6. Conclusion

Augmented reality (AR) holds great potential for enhancing environmental education in Algeria by providing an interactive and immersive learning experience that helps clarify abstract environmental concepts and promotes sustainable behaviors among youth. However, its successful implementation depends on systematic integration into national curricula, improved digital infrastructure, and teacher training to ensure effective use in schools and universities. Several challenges hinder the widespread adoption of AR, including limited access to compatible devices, weak internet connectivity, and high battery and data consumption, particularly in rural and underserved areas. Additionally, cognitive overload and overly complex interactions can reduce learning efficiency, requiring a balanced and user-friendly design. Cultural adaptation is another critical factor, as AR content must be locally relevant, addressing Algeria's specific environmental challenges and available in multiple languages to ensure accessibility for diverse learners.

For AR to drive lasting behavioral change, future research should focus on long-term impact studies to assess whether environmental behaviors persist over time. Comparative studies should also evaluate AR against other digital learning tools, such as virtual reality (VR) and gamified learning applications,

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to determine the most effective approaches for fostering environmental awareness and action. To maximize AR's impact, strong government policies, interdisciplinary collaboration, and localized content development are essential. By addressing technological barriers, refining educational methodologies, and ensuring equitable access, AR can play a pivotal role in shaping an environmentally conscious generation in Algeria, equipping them with the knowledge and motivation to tackle pressing sustainability challenges.

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