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Augmented Reality Applications for Enhancing Environmental Awareness in Smart Tourism: A Systematic Literature Review

Victor Marudut Mulia Siregar[1], Andi Setiadi Manalu[2], Roy Sahputra Saragih[3]

[1-3] Politeknik Bisnis Indonesia, Pematang Siantar, Indonesia

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ABSTRACT

Augmented Reality (AR) has been increasingly adopted in smart tourism to enhance visitor experiences and support sustainability-oriented learning. However, empirical evidence regarding how AR applications contribute to environmental awareness and sustainable tourism practices remains fragmented and insufficiently synthesized. This study conducts a systematic literature review to examine the role of AR in enhancing environmental awareness within smart tourism contexts and its potential contribution to sustainability-oriented tourism development. The review addresses three research questions concerning the implementation of AR applications for environmental learning, the comparative effectiveness of AR and non-AR approaches, and the key challenges and research opportunities associated with AR in sustainability-oriented tourism. The review follows the PICOC framework (Population, Intervention, Comparison, Outcome, Context) and PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. A structured search of the Scopus database covering publications from 2022 to 2025 resulted in 32 empirical journal articles included in the final analysis. The findings indicate that AR applications, such as mobile AR systems, location-based interpretation, immersive environmental visualization, and gamified learning tools, are widely implemented in tourism environments including museums, heritage sites, geotourism destinations, natural parks, and wildlife attractions. Overall, AR tends to enhance environmental understanding, emotional engagement, and pro-environmental intentions more effectively than conventional interpretation media. These outcomes contribute to strengthening visitor awareness of environmental conservation and responsible tourism behavior. This review synthesizes fragmented empirical evidence and highlights key methodological and technological gaps while outlining future research directions for advancing AR-based environmental learning and sustainability practices within smart tourism ecosystems.

Corresponding Author:

Victor Marudut Mulia Siregar,
Computer Engineering,
Politeknik Bisnis Indonesia,
Pematangsiantar City, North Sumatra, Indonesia
Email: victor.siregar2@gmail.com

1. INTRODUCTION

The rapid expansion of global tourism has generated substantial economic benefits across many countries. However, this growth has also intensified environmental pressures on fragile ecosystems, protected areas, and cultural heritage sites. Tourism activities contribute to various environmental impacts, including biodiversity disturbance, landscape degradation, pollution, and increasing pressure on ecological carrying capacities in many tourist destinations [1], [2], [3], [4], [5]. In addition, the development of tourism infrastructure significantly contributes to greenhouse gas emissions, further exacerbating environmental challenges associated with the expansion of the tourism sector [6]. Although sustainability issues have long been discussed in tourism research, tourism development often continues to prioritize economic growth over environmental protection and social equityl [7], [8]. This situation highlights the importance of tourism management strategies that enhance environmental awareness and encourage responsible visitor behavior in order to support sustainable tourism development.

Advances in digital technologies have also driven digital transformation in the tourism sector, giving rise to the concept of smart tourism, which integrates information technology, data, and tourism experiences to create more innovative and sustainable destinations [9], [10], [11]. One technology that has received significant attention in the development of smart tourism is Augmented Reality (AR). This technology enables the integration of digital information with the physical environment, thereby creating tourism experiences that are more informative, interactive, and immersive [12], [13], [14], [15]. AR enables tourists to visualize environmental phenomena, access contextual ecological information, and interpret destination narratives on-site [16], [17].

Beyond enhancing visual appeal and entertainment value, AR has demonstrated strategic value in environmental education, cultural heritage preservation, and the promotion of sustainable tourism behavior through adaptive, narrative-driven, and location-based information delivery [18], [19], [20]. Through mobile-based systems technologies, AR applications can present environmental and cultural heritage information in more engaging ways while supporting experiential learning among visitors [21], [22], [23].

Several studies indicate that immersive technologies such as AR can enhance tourist engagement and enrich overall tourism experiences [24], [25]. From an environmental sustainability perspective, AR also has the potential to increase tourists' environmental awareness through the visual and interactive presentation of environmental information [26]. Empirical studies show that AR-based tourism experiences can strengthen tourists' environmental values and encourage pro-environmental behavior by improving their understanding of environmental issues and their sense of responsibility toward sustainability [27]. Furthermore, AR technologies can visualize environmental data in real time, such as air quality or biodiversity information, thereby helping visitors better understand environmental conditions and encouraging conservation-oriented tourism practices [28]. In ecotourism contexts, immersive AR platforms have also demonstrated potential to strengthen visitor engagement with conservation messages and enhance sustainability-oriented tourism experiences [12], [29].

Despite the rapid growth of research on the application of Augmented Reality in tourism over recent years, most studies primarily focus on improving tourist experiences, visitor satisfaction, and technology adoption. Research specifically examining the role of AR in enhancing environmental awareness and pro-environmental behavior among tourists remains relatively limited and presents inconsistent findings [30], [31]. Moreover, many studies employ survey-based quantitative approaches using SEM or PLS-SEM methods, which may not adequately capture the contextual dynamics and experiential aspects of tourists' interactions with AR-based environmental content [27], [32]. Existing research is also frequently conducted within specific destinations or geographic regions, which limits the generalizability of findings across diverse tourism environments [11], [31]. In addition, longitudinal studies examining the long-term impact of AR experiences on environmental awareness and behavioral change among tourists remain scarce. Furthermore, theoretical integration between technology adoption models and environmental behavior frameworks has not yet been sufficiently developed in the current literature [33], [34].

Given these limitations, a systematic synthesis of existing studies is necessary to integrate fragmented empirical findings and provide a more comprehensive understanding of the role of AR technologies in enhancing environmental awareness within smart tourism ecosystems. The systematic literature review method offers a structured and comprehensive approach for identifying research trends, evaluating methodological approaches, and synthesizing theoretical frameworks from relevant studies.

Therefore, this study conducts a systematic literature review to examine the application of Augmented Reality technologies in enhancing environmental awareness within the context of smart tourism. Specifically, the study aims to synthesize empirical findings on AR-based tourism applications, evaluate their effectiveness in improving environmental awareness and pro-environmental behavior among tourists, and identify research gaps and future research directions to support the development of sustainability-oriented smart tourism.

2. RESEARCH METHOD

2.1. Identification Phase

This study adopts a systematic literature review (SLR) to synthesize existing research on the role of Augmented Reality (AR) in enhancing environmental awareness within smart tourism contexts. Systematic literature reviews provide a rigorous and transparent method for identifying, evaluating, and synthesizing evidence from existing studies, thereby enabling researchers to consolidate fragmented knowledge and identify emerging research patterns within a particular field. Compared with traditional narrative reviews, the SLR approach follows a structured and replicable procedure that minimizes selection bias and enhances methodological transparency.

The review in this study is positioned as a thematic synthesis-oriented systematic review, aiming to identify research trends, methodological approaches, and conceptual insights related to AR applications for environmental awareness in tourism environments. To ensure transparency and reproducibility, the review process follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, which provides standardized guidelines for identifying, screening, and selecting relevant literature.

2.2. PICOC Framework and Research Questions (RQ)

To ensure methodological rigor, the research questions guiding this review were formulated using the PICOC framework (Population, Intervention, Comparison, Outcome, and Context), which is widely used in systematic evidence-based research to structure review questions and define the scope of literature searches [35]. The PICOC framework applied in this study is summarized in Table 1.

Table 1. Picoc Framework

PICOC Element	Description
Population	Tourists and visitors participating in tourism experiences
Intervention	Augmented Reality applications used in tourism environments
Comparison	Conventional tourism interpretation methods or non-AR approaches
Outcome	Environmental awareness, environmental learning, and pro-environmental behavior
Context	Smart tourism destinations and tourism-related environments

Based on this framework, the review addresses the following research questions:

- **RQ1:** How are AR applications implemented to enhance ecological literacy and environmental awareness within smart tourism contexts?
- **RQ2:** To what extent is AR more effective than non-AR approaches in improving environmental understanding, emotional engagement, and sustainable behavioral intention?
- **RQ3:** What challenges and research opportunities arise in using AR for sustainability tourism?

2.3. Search Strategy and Data Sources

A systematic search was conducted to identify relevant studies examining the application of Augmented Reality for environmental awareness in tourism. The literature search was conducted using the Scopus database. Scopus was selected due to its extensive coverage of high-quality peer-reviewed publications and its frequent use as a primary data source in systematic literature reviews within tourism and information systems research.

The literature search was conducted on 15 December 2025 using combinations of keywords related to Augmented Reality, environmental awareness, and tourism. Boolean operators were used to combine keywords in order to capture relevant publications while minimizing irrelevant results. The search string used in this study is presented below:

(TITLE-ABS-KEY("augmented reality" OR "AR" OR "mobile augmented reality"
OR "mixed reality" OR "extended reality" OR "XR"))
AND
(TITLE-ABS-KEY("environment*" OR "sustainab*" OR "eco-awareness"
OR "environmental awareness" OR "environmental education"
OR "environmental engagement" OR "sustainable behavior"))
AND
(TITLE-ABS-KEY("touris*" OR "smart tourism" OR "sustainable tourism"
OR "eco-tourism" OR "ecotourism" OR "tourist experience"
OR "destination" OR "heritage site" OR "natural park"))

2.4. Inclusion and Exclusion Criteria

To ensure the relevance and quality of the selected studies, a set of inclusion and exclusion criteria was established prior to the literature screening process. These criteria were designed to focus the review on empirical studies examining the role of Augmented Reality in tourism contexts, particularly those addressing environmental awareness and sustainability-related outcomes. The inclusion criteria are presented in Table 2.

Table 2. Inclusion And Exclusion Criteria

Phase	Inclusion Criteria	Exclusion Criteria
Identification	• Published 2022–2025 • Written in English	• Published outside 2022–2025
Screening	• Focuses on environmental awareness, environmental education, or sustainability • Uses AR technology	• SLR/review papers, Conference notes, speaker notes Does not use AR • Not related to environmental awareness or sustainability
Eligibility	• Full-text available	-

2.5. Quality Assessment

The quality of the selected studies was assessed using a structured Quality Checklist (QC) to ensure their relevance, methodological rigor, and credibility in addressing the research objectives. The checklist, comprises a set of evaluative questions designed to examine the clarity of research aims, appropriateness of study design, transparency of data collection and AR implementation, and robustness of reported findings.

Specifically, the Quality Checklist includes four assessment criteria: (QC1) whether the research objectives are clearly stated, specific, and relevant to the context of Augmented Reality (AR) and sustainable tourism; (QC2) whether the research design is appropriately aligned with the stated objectives and capable of addressing the proposed research questions; (QC3) whether the data collection procedures, study context, and AR implementation are described in sufficient detail to allow methodological replication; and (QC4) whether the research findings and their interpretations are clearly presented and supported by adequate empirical evidence.

Each criterion was scored as follows: 1 if the study provides a clear and comprehensive response, 0.5 if the study addresses the criterion partially, and 0 if the study does not address the criterion at all. This scoring procedure follows established quality assessment guidelines adopted in prior SLR studies [36], [37], [38]. A minimum threshold score of 3.0 was applied to determine whether a study met the required quality standards for inclusion in the final synthesis.

2.6. Screening Phase

The systematic literature review (SLR) followed the PRISMA 2020 guidelines to ensure methodological transparency and reproducibility [39], [40], [41]. The initial database search identified 1,163 records. After applying the publication year restriction (2022–2025), 674 records remained. The screening process was then limited to documents classified as journal articles, resulting in 235 records. Subsequently, additional eligibility criteria were applied, including journal sources, English-language publications, and final publication status, which yielded 210 eligible records. A full-text screening and quality assessment were then conducted. Based on the predefined inclusion threshold (QC ≥ 3), 32 studies were ultimately included in the final review. The overall study selection process is illustrated in Figure 1.

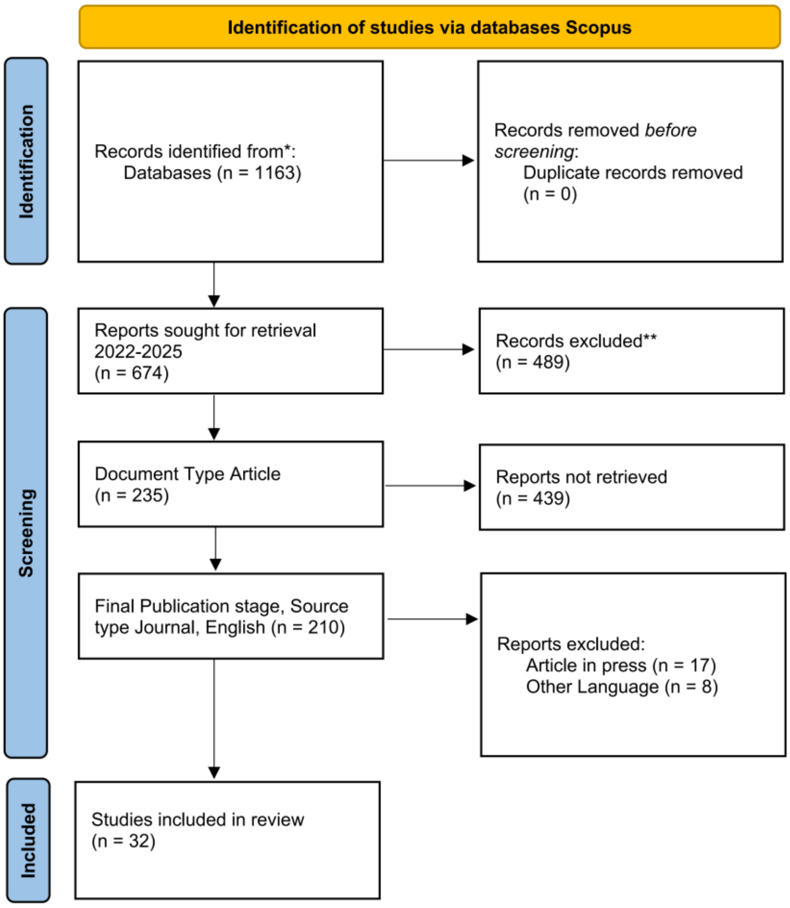

Figure 1. PRISMA Flowchart

3. RESULTS AND DISCUSSIONS

3.1. Characteristics of Included Studies

A total of 32 studies met the predefined inclusion criteria and quality assessment threshold and were included in the final analysis. All selected publications were published between 2022 and 2025, reflecting the growing scholarly interest in immersive technologies, particularly Augmented Reality (AR), within smart tourism and sustainability-related research.

The reviewed studies were conducted across several geographical regions, including Europe, Asia, and the Americas, although the distribution remains uneven. The geographical distribution of publications is illustrated in Figure 2, which shows the number of studies by country. Countries such as Spain, China, and the United States account for a substantial proportion of the reviewed studies.

Many studies were conducted in destinations with well-established smart tourism initiatives and advanced digital infrastructures, whereas relatively few were undertaken in developing tourism regions. This pattern indicates a geographical imbalance in the current literature and highlights the need for broader empirical investigations across diverse tourism contexts.

AR technologies have been applied in various tourism environments, including cultural heritage sites, museums, natural parks, and ecotourism destinations. In heritage settings, AR is often used to reconstruct historical environments, visualize lost architectural elements, and deliver contextual storytelling that enhances visitors' cultural understanding. In nature-based tourism contexts such as national parks and protected areas, AR applications typically communicate ecological information, biodiversity interpretation, and environmental narratives aimed at strengthening conservation awareness.

Most studies examined mobile-based AR applications delivered through smartphones or tablets using location-based services or image-recognition technologies, reflecting their accessibility and compatibility with existing tourism infrastructures. A smaller number of studies explored more advanced immersive environments such as mixed reality (MR) and extended reality (XR), although their practical adoption in tourism remains limited due to higher technological complexity and development costs.

Overall, the reviewed literature demonstrates the growing adoption of AR technologies across tourism contexts, particularly in destinations with strong digital infrastructures. However, the geographical concentration of existing studies suggests the need for further research exploring AR applications in a broader range of tourism environments and socio-cultural contexts.

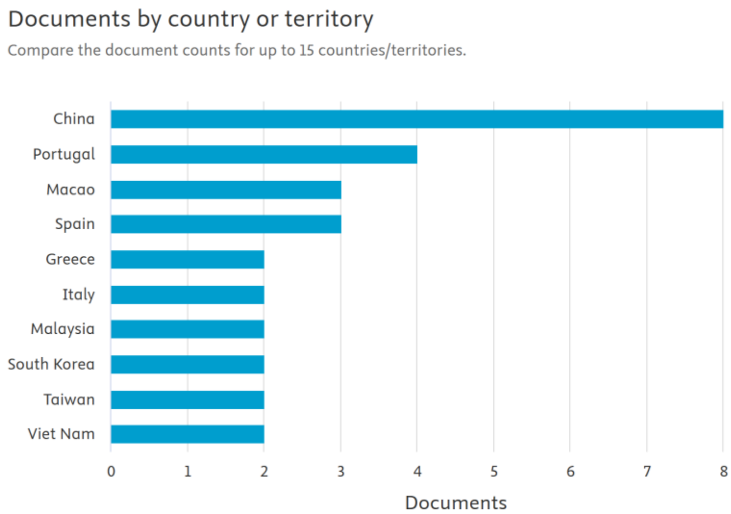

Figure 2. Documents by country

3.2. Findings Based on Research Questions

RQ1: How are AR applications implemented to enhance ecological literacy and environmental awareness within smart tourism contexts?

The reviewed studies indicate that Augmented Reality (AR) is increasingly used as a digital interpretation tool to enhance ecological literacy and environmental awareness across diverse tourism settings, including green tourism destinations, geotourism sites, museums, cultural heritage locations, wildlife attractions, and environmental education environments. By integrating digital information with real-world environments, AR enables visitors to engage with environmental content through immersive and context-aware visualizations that support experiential learning.

Across the literature, AR implementations generally follow several application patterns. First, AR is widely used for environmental interpretation and ecological visualization, where digital overlays communicate information about biodiversity, ecosystems, and geological heritage in natural parks and protected areas. Second, AR supports heritage-based environmental storytelling, allowing visitors to explore reconstructed historical landscapes and cultural heritage while conveying sustainability messages. Third, AR is applied in interactive environmental education, including museum exhibitions, gamified learning tools, and wildlife interpretation systems that increase engagement with ecological content. Some studies also employ AR to visualize environmental change, such as climate change impacts or fragile ecosystems, helping visitors understand environmental processes that are difficult to observe directly.

Overall, the reviewed studies suggest that AR enhances environmental communication by combining immersive visualization, location-based information, and narrative-driven experiences. These features can increase visitor engagement, improve environmental understanding, and strengthen emotional connections with natural environments, thereby supporting ecological literacy and sustainability awareness within smart tourism ecosystems. These findings indicate that AR applications function not only as interpretive tools but also as experiential learning environments that connect environmental information with place-based tourism experiences. Table 3 summarizes the main AR application contexts, implementation approaches, and environmental awareness outcomes identified in the reviewed studies.

Table 3. Summary of AR Applications for Enhancing Ecological Literacy and Environmental Awareness

No	Tourism / Environmental Context	AR Implementation	Outcomes Related to RQ1	Reference
1	Green tourism (Vietnam)	Mobile AR tourism app	Enhanced green experience and eco-intention	[34]
2	Cultural festivals & sustainability	AR interactive learning materials	Increased engagement and understanding of cultural sustainability	[42]
3	Marine conservation museum	AR marine exhibition	Improved awareness of consequences and pro-environmental norms	[43]
4	Metaverse tourism & overtourism	AR within metaverse platforms	Supported tourism dispersion and sustainability awareness	[44]
5	Digital heritage	AR for 3D heritage objects	Improved ecological understanding and reduced physical site damage	[45]
6	Ocean literacy	AR board game	Increased ocean literacy and environmental awareness	[46]
7	Safari & wildlife education	AR animal information app	Strengthened emotional connection and eco-engagement	[47]
8	Regenerative tourism	Immersive AR journalism	Enhanced eco-literacy and pro-environmental behavior	[48]
9	Geotourism (Arosa Estuary)	AR + virtual 3D flights	Increased geoheritage awareness	[49]
10	Forest park	AR flora–fauna interpretation	Strengthened memorable eco-experiences	[21]
11	Natural park (Spain)	AR virtual itineraries	Improved geoconservation attitudes and ecological interpretation	[50]
12	Hiking trail ecosystems	ARCore-based trail guide	Increased awareness of local biodiversity	[51]
13	Wildlife tourism	AR hologram zoo	Enhanced ecological empathy	[52]
14	Inaccessible heritage sites	Location-based AR	Strengthened appreciation of environmental heritage	[53]
15	Climate change impacts	LiDAR-based AR climate visualization	Increased awareness and empathy toward climate change	[54]
16	Urban geo-scientific heritage	AR for naturalistic points of interest	Enhanced understanding of urban geoscience and naturalistic values	[55]
17	Family ecotourism	AR nature exploration apps	Strengthened sustainability education	[56]
18	Museum heritage	AR exploration mirror	Increased heritage-responsibility behavior	[57]
19	Cultural revitalization	AR stylized heritage models	Enhanced engagement and environmental appreciation	[58]
20	Wildlife conservation	AR realistic animal simulation	Improved ecological understanding and awareness	[59]

No	Tourism / Environmental Context	AR Implementation	Outcomes Related to RQ1	Reference
21	Ecotourism destinations (India national parks)	AR/VR immersive environmental interpretation	Strengthened telepresence, emotional engagement, and intention toward responsible ecotourism and conservation behavior	[60]
22	Marine museum environmental education (China)	AR-supported museum exhibition	Strengthened personal norms, environmental attitudes, and pro-environmental behavioral intentions	[61]

RQ2. To what extent is AR more effective than non-AR approaches in improving environmental understanding, emotional engagement, and sustainable behavioral intention?

Comparative evidence from the reviewed studies suggests that Augmented Reality (AR) often provides advantages over conventional non-AR approaches in promoting environmental understanding, emotional engagement, and pro-environmental behavioral intentions. By integrating interactive digital overlays with real-world environments, AR enables users to explore ecological information in more contextualized and experiential ways than traditional interpretive media.

Several experimental and quasi-experimental studies indicate that AR can improve environmental knowledge acquisition, learning motivation, and perceived educational value. For instance, AR-based educational games and interactive learning tools have been shown to enhance environmental awareness, attitudes, and behavioral engagement compared with lecture-based or static visual methods. Similarly, AR-enhanced interpretation systems can strengthen emotional connections with environmental issues by visualizing otherwise invisible phenomena such as climate change impacts, endangered ecosystems, or inaccessible geoheritage sites.

However, the comparative effectiveness of AR is not universal. Some studies suggest that direct real-world experiences may produce stronger conservation outcomes when they involve highly immersive physical interaction with natural environments. In such cases, AR functions primarily as a complementary interpretive tool rather than a complete substitute for experiential environmental learning.

Overall, the reviewed evidence indicates that AR can significantly enhance environmental communication and sustainability learning in tourism contexts, particularly when immersive visualization, interactive design, and contextual storytelling are effectively integrated. While AR frequently demonstrates advantages over conventional media in terms of engagement and knowledge acquisition, its effectiveness ultimately depends on the quality of instructional design and the degree to which the technology is embedded within meaningful environmental learning experiences. Table 4 summarizes the comparative findings between AR and non-AR approaches reported in the reviewed studies, highlighting their relative effectiveness in enhancing environmental understanding and engagement.

Table 4. Summary of Comparative Findings Between AR and Non-AR Approaches

No.	Study	Type of Comparison	Key Findings	Evidence of AR Effectiveness
1	AR board game vs. traditional lecture [46]	Direct (experiment)	AR significantly increases knowledge, awareness, attitudes, activism, and behavior compared with traditional lectures.	AR is considerably more effective in enhancing environmental literacy.
2	AR treasure hunt vs. VR tour [62]	Direct	AR yields higher scores in behavioral intention, learning effect, and user satisfaction.	AR is more flexible and effective; VR is slower and more complex.
3	AR for endangered cultural site vs. static visual media [54]	Direct (psychological effect)	AR increases emotional attachment, empathy, and contextual understanding.	AR is superior in emotional connection and climate-change comprehension.
4	Hologram Zoo (AR) vs. Shark Dive (non-AR) [52]	Narrative comparison	AR improves visual representation but is less effective for conservation outcomes than Shark Dive.	AR is not always superior; effectiveness depends on educational content.

No.	Study	Type of Comparison	Key Findings	Evidence of AR Effectiveness
5	AR lantern exhibition vs. traditional method (implicit) [63]	Indirect	AR enhances learning motivation and cultural awareness.	AR strengthens motivation even without direct comparison.
6	Web-based AR vs. non-AR marketing (proposed) [64]	Indirect	AR increases visit intention, immersion, and enjoyment.	Indicates higher effectiveness of AR; experimental validation needed.
7	AR vs. traditional heritage learning (implicit) [57]	Indirect	AR increases perceived usefulness, enjoyment, and behavioral intention.	AR is more impactful for promoting heritage responsibility.
8	AR fur simulation vs. traditional wildlife display [59]	Technical comparison	AR improves realism and conservation education in a non-invasive manner.	AR is more effective for wildlife education.
9	AR vs. non-AR geotourism interpretation [65]	Conceptual comparison	AR is more effective for interpreting "lost" or inaccessible geoheritage sites.	AR excels in contextualized geoheritage interpretation.

RQ3. What challenges and research opportunities arise in using AR for sustainability tourism?

The reviewed studies reveal several challenges associated with the implementation of Augmented Reality (AR) in sustainability-oriented tourism contexts. These challenges can be broadly grouped into technical limitations, design and user experience issues, and methodological constraints. Technical limitations frequently include unstable image tracking, low geolocation accuracy, heavy rendering loads, and inconsistent performance across devices, which may reduce system reliability in real tourism environments. Design-related limitations include insufficient educational depth, weak narrative structures, and limited interaction features that can restrict user engagement and learning effectiveness. In addition, disparities in digital literacy among users may affect the accessibility and usability of AR-based tourism applications.

From a methodological perspective, much of the existing research relies on cross-sectional survey designs based on self-reported measures, often involving small or homogeneous samples. Such limitations restrict the generalizability of findings and make it difficult to determine whether AR experiences lead to sustained pro-environmental behavioral change over time.

Despite these challenges, the literature also highlights several promising research opportunities. Future studies may explore the integration of AR with artificial intelligence and machine learning to support adaptive environmental learning and behavioral prediction. Other directions include the development of narrative-driven and empathy-based AR experiences, multi-user environments that facilitate collaborative eco-learning, and hybrid systems combining immersive visualization with environmental monitoring technologies. Furthermore, cross-cultural replications, multi-site comparative studies, and longitudinal research designs are needed to better assess the long-term behavioral impacts of AR-based sustainability interventions.

The key challenges and corresponding research opportunities identified in the reviewed studies are summarized in Table 5. These findings highlight the need for interdisciplinary collaboration between tourism researchers, technology developers, and sustainability practitioners to design AR systems that effectively support environmental learning and pro-environmental behavioral change.

Table 5. Summary Of Challenges and Research Opportunities for AR In Sustainability Tourism

No.	Key Challenges	Research Opportunities & Directions	Reference
1	Self-report bias; cross-sectional design	Longitudinal studies; multi-destination comparisons	[34]
2	Declining youth interest; cultural revitalization difficulty	AR for ICH preservation; multi-user AR; experiential learning	[42]
3	Single museum context; non-significant presence/flow	Cross-cultural studies; examining presence & authenticity	[66]
4	Homogeneous samples; immersion not evaluated	Cross-cultural research; integrating immersion & emotion	[44]

5	High scanning cost; limited heritage data	Low-cost technologies; heritage reconstruction pipelines	[45]
6	Small samples; intended (not actual) behavior	Longitudinal designs; real behavioral measurements	[46]
7	AR fails user expectations (e.g., animal sounds)	AR narrative design; personalization of AR	[47]
8	Social bias; no experiment	Immersive journalism AR for eco-literacy	[48]
9	Geosite degradation risks; conservation needs	AR for environmental monitoring & geoconservation	[49]
10	Subjectivity of AR experience	AR–metaverse integration; personalized memorable tourism experiences	[55]
11	Complexity in geosite assessment	AR for geological pedagogy; multi-layer interpretation	[50]
12	Poor tracking; low geolocation accuracy	Offline AR; hybrid tracking; stable AR navigation	[51]
13	Lack of conservation messaging	AR storytelling for wildlife ethics & conservation	[52]
14	Financial constraints; weak business models	AR for entrepreneurship & creative tourism	[67]
15	Low-precision mobile LiDAR; vegetation rendering issues	AR time-series visualization; conservation-empathy design	[54]
16	Poor documentation; limited data	AR for "lost sites"; digital landscape resurrection	[65]
17	Low dependability & efficiency	Iterative AR design; multi-target performance testing	[68]
18	Low sensor accuracy; unstable UI	Markerless AR + geofencing; UX refinements	[53]
19	Single-site sampling; regional bias	Multi-site comparative AR studies; cross-regional analysis	[69]
20	Low AR budget; low AVE	Controlled AR vs. non-AR experimental design	[64]
21	Uneven age representation; authenticity concerns	AR authenticity modelling; elderly-inclusive AR	[57]
22	Digital divide; small samples	AIGC + AR for heritage gamification	[58]
23	Heavy rendering load; limited fur realism	AR + AI for autonomous wildlife behavior	[59]
24	Low interaction; weak content depth	AR leveling systems; adaptive storytelling	[70]
25	Bureaucratic issues; inconsistent data	Integrated AR heritage data environments	[71]
26	Small sample; subjective responses	Objective measures; expanding ICH contexts	[63]
27	VR limitations; AR superior in several cases	AR-based gamified eco-learning frameworks	[62]
28	Unstable image targets	AR for dynamic naturalistic elements	[55]
29	High cost; data ethics concerns	AR for post-war restoration; metadata registry	[72]
30	Small samples; elderly-focused contexts	AR interventions for family-based ecotourism	[56]
31	Limited exposure to AR/VR technologies; qualitative design with restricted generalizability	Empirical validation of AR/VR models; cross-cultural replication; repeated exposure studies to assess behavioral change	[60]
32	Single-site museum context; non-significant effects of presence and flow experience	Cross-context comparative studies; examining interaction design, authenticity, and knowledge acquisition in AR-based environmental learning	[61]

3.3. Discussion

This section interprets the key findings of the systematic literature review by examining how Augmented Reality (AR) contributes to environmental awareness in sustainable smart tourism. The discussion synthesizes evidence regarding the role of AR in enhancing ecological literacy (RQ1), evaluates its comparative effectiveness against conventional interpretation approaches (RQ2), and identifies key challenges and future research opportunities shaping AR adoption in sustainability-oriented tourism (RQ3).

3.3.1. Integration and Role of AR in Enhancing Ecological Literacy (RQ1)

The reviewed studies indicate that immersive digital overlays enable visitors to engage with environmental knowledge in ways that are more contextualized and experiential than conventional interpretation methods. By embedding digital information directly into physical tourism environments, AR allows users to visualize ecological processes, environmental risks, and conservation issues that are often difficult to observe through traditional media.

Interactive visualization reduces the abstraction of complex ecological concepts and facilitates experiential learning, which improves visitors' understanding of ecosystem dynamics and sustainability challenges. In addition, the integration of narrative storytelling, simulation, and real-time environmental visualization strengthens emotional engagement and ecological empathy, both of which are important drivers of environmentally responsible behavior.

These mechanisms are consistent with theoretical perspectives such as the Technology Acceptance Model (TAM) and Norm Activation Theory (NAT). When AR experiences provide perceived usefulness, enjoyment, and immersive interaction, they tend to increase user engagement and environmental concern, which may activate personal norms and encourage pro-environmental behavioral intentions. Overall, the evidence suggests that AR enhances ecological literacy through the combined effects of immersive visualization, contextualized experiential learning, and emotionally engaging environmental narratives.

3.3.2. Effectiveness of AR Compared with Non-AR Approaches (RQ2)

Comparative evidence indicates that AR-based interpretation frequently produces stronger outcomes in environmental learning and engagement than conventional communication approaches such as static media or lecture-based explanations. The integration of interactive visualization with real-world contexts enables visitors to explore ecological information in a more embodied and intuitive manner, which contributes to improved knowledge acquisition and greater visitor satisfaction.

The advantages of AR are largely associated with its technological affordances, including interactivity, visual vividness, and contextual integration with physical environments. These features enable users to connect environmental information directly with the surrounding landscape, strengthening both cognitive understanding and emotional responses to sustainability issues.

Nevertheless, the effectiveness of AR remains contingent upon the quality of system design and content development. Studies report diminished impacts when AR systems suffer from unstable tracking, limited content depth, or poorly designed user interfaces. In addition, differences in users' digital familiarity can influence the effectiveness of AR-based learning experiences. Despite these constraints, the overall evidence suggests that well-designed AR systems can provide more engaging and impactful environmental communication than traditional interpretation approaches.

3.3.3. Key Challenges and Future Opportunities for AR in Sustainability Tourism (RQ3)

The literature identifies several barriers that continue to limit the wider implementation of AR in sustainability-oriented tourism environments. These barriers can be broadly grouped into technical limitations, usability and accessibility issues, and methodological constraints. Technical challenges include unstable tracking performance, limited LiDAR precision, inconsistent image recognition in outdoor settings, and high computational demands that can affect system reliability. Usability challenges involve insufficient interaction depth, limited conservation messaging, and variations in digital literacy among different visitor groups.

From a methodological perspective, many studies rely on cross-sectional surveys and self-reported perceptions based on relatively small or homogeneous samples. Such limitations reduce the generalizability of findings and restrict the ability to evaluate whether AR experiences lead to sustained behavioral change. Furthermore, many applications lack integration with scientifically grounded environmental data, which may limit the depth of environmental interpretation provided to visitors.

At the same time, the literature highlights several promising research directions. Future studies may explore the development of AR frameworks that support long-term environmental learning and behavioral transformation, as well as the expansion of AR applications into areas such as waste management, environmental monitoring, and conservation education. Integrating AR with LiDAR, GIS, IoT, and artificial intelligence may also enable more data-driven environmental interpretation. In addition, longitudinal and mixed-method research designs are needed to better evaluate the long-term behavioral impacts of AR-based environmental experiences.

3.3.4. Theoretical and Practical Implications

The findings contribute to the literature by synthesizing fragmented empirical evidence and clarifying the mechanisms through which immersive technologies influence environmental awareness in tourism contexts. Integrating technology adoption theories, such as the Technology Acceptance Model (TAM) and Unified Theory of Acceptance and Use of Technology (UTAUT), with environmental behavior frameworks, including Norm Activation Theory (NAT) and the Theory of Planned Behavior (TPB), may provide a more comprehensive explanation of how digital experiences translate into environmental cognition and behavioral change.

From a practical perspective, immersive technologies offer significant opportunities for improving sustainability communication in tourism destinations. Destination managers, tourism authorities, and conservation organizations can use AR-based interpretation systems to communicate environmental information more effectively, promote responsible visitor behavior, and enhance the protection of environmentally sensitive sites. As digital infrastructures continue to expand, AR technologies may become an important component of sustainability strategies within smart tourism ecosystems.

3.3.5. Limitations And Future Works

Several limitations should be acknowledged. The review relied exclusively on the Scopus database, which may have excluded relevant studies indexed in other specialized databases such as IEEE Xplore or ACM Digital Library. The focus on publications from 2022–2025 ensured the inclusion of recent research but may have overlooked earlier foundational studies related to the development of AR for environmental education. In addition, the exclusion of conference papers may have limited insights into emerging technological innovations that are often first introduced in technology-oriented venues.

Considerable heterogeneity across AR technologies, evaluation approaches, and participant characteristics also prevented quantitative meta-analysis. Much of the existing evidence relies on cross-sectional research and self-reported perceptions, which provide limited insight into long-term behavioral change. Sample sizes are often small and context-specific, reducing the generalizability of findings across diverse tourism environments.

Future research should therefore prioritize longitudinal and mixed-method studies capable of evaluating sustained ecological behavior change rather than short-term attitudinal responses. Cross-cultural and multi-site investigations are also necessary to understand sociotechnical factors influencing AR adoption and environmental learning. Further technological development should focus on improving tracking robustness, adaptive AI-driven interaction, and lightweight AR architectures suitable for outdoor tourism environments. Expanding AR applications into emerging domains such as clean-tourism initiatives, climate-risk visualization, geoconservation, and indigenous ecological knowledge interpretation may further strengthen the role of immersive technologies in supporting sustainable tourism development.

4. CONCLUSION

This systematic literature review examines how Augmented Reality (AR) applications enhance environmental awareness within smart tourism contexts. The findings indicate that AR is increasingly adopted as an immersive environmental interpretation tool across diverse tourism settings, including museums, heritage sites, natural parks, and ecotourism destinations. Through location-based visualization, interactive storytelling, and contextual environmental information, AR enables visitors to understand ecological processes and sustainability challenges more effectively than conventional interpretation approaches. The evidence suggests that AR-based applications frequently generate stronger cognitive and affective outcomes than traditional methods, particularly in improving environmental understanding, visitor engagement, and sustainability awareness. These advantages stem from AR's ability to integrate digital environmental information directly into real-world tourism environments, supporting contextual and experiential learning. However, their effectiveness remains dependent on technological reliability, content design, and interaction quality. Moreover, the predominance of cross-sectional studies and self-reported measures limits current understanding of long-term pro-environmental behavioral change among tourists. This review contributes to the literature by synthesizing fragmented empirical evidence and clarifying how immersive technologies facilitate environmental learning within smart tourism ecosystems. The findings highlight the potential of AR applications as contextual tools for sustainability communication while also revealing methodological and technological gaps in current research. Future studies should prioritize longitudinal and mixed-method approaches to evaluate sustained behavioral outcomes. Integrating AR with environmental data infrastructures such as GIS, LiDAR, IoT, and adaptive artificial intelligence may further enhance the ecological validity, scalability, and practical impact of AR-based sustainability initiatives in tourism destinations.

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DECLARATIONS

AI USAGE STATEMENT

The authors declare that AI-assisted technologies ChatGPT were used to support the drafting and editing of this manuscript, specifically in refining grammar, improving sentence clarity, and checking coherence. No part of the conceptual framework, data interpretation, or conclusions was generated by AI. The authors have thoroughly reviewed and verified all content, and accept full responsibility for the work presented.

AUTHOR CONTRIBUTION

Victor Marudut Mulia Siregar: Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing, Supervision. Andi Setiadi Manalu: Methodology, Writing - Review & Editing, Supervision. Roy Sahputra Saragih: Methodology, Writing - Review & Editing, Supervision.

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CONFLICTING INTERESTS

The authors declare no conflict of interest.

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