

Digital Innovation in Sustainable Nature-Based Tourism: A Literature Review

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This study systematically reviews the application of geographic information systems, decision support systems, artificial intelligence, augmented reality, and virtual reality within the context of sustainable tourism in natural environments. The findings reveal that geographic information systems and decision support systems are fundamental for spatial decision-making and conservation planning. At the same time, artificial intelligence facilitates real-time visitor management, and augmented and virtual reality enrich educational and immersive experiences that foster environmental awareness. Nevertheless, challenges such as limited infrastructure, regulatory gaps, and barriers to technological accessibility remain, particularly in remote and developing regions. This review emphasises the need for integrated hybrid models, such as artificial intelligence-powered geographic information systems for predictive environmental assessments and virtual reality-enhanced decision support systems for simulating visitor flows in protected areas. Future research should focus on developing scalable and context-sensitive frameworks for technology adoption in nature-based destinations. Collaboration among policymakers, industry stakeholders, and researchers is essential to establish regulatory standards, promote digital inclusion, and foster interdisciplinary partnerships that ensure digital innovations effectively contribute to the sustainable development and stewardship of natural tourism sites.

Keywords: artificial intelligence, augmented reality, decision support systems, sustainable tourism, virtual reality



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Introduction

Sustainable nature-based tourism has become a global priority in the management of natural destinations, as it promotes biodiversity conservation, local economic development, and the well-being of host communities (Bahou et al., 2024; Costantino et al., 2024; Mandić, 2019). Although related, nature-based tourism, ecot-

ourism, and sustainable tourism are not interchangeable concepts. Nature-based tourism broadly refers to travel experiences in natural environments (Mandić, 2019), ecotourism places greater emphasis on environmental education and minimal impact (Costantino et al., 2024), and sustainable tourism provides an overarching framework that integrates environmen-

tal, social, and economic goals (Bahou et al., 2024). In this study, we focus specifically on sustainable nature-based tourism, understood as tourism activities in natural settings that are developed under sustainability principles.

The integration of digital technologies has reshaped how destinations are planned, managed, and experienced. Geographic information systems (GIS), decision support systems (DSS), artificial intelligence (AI), augmented and virtual reality (AR/VR), and blockchain are increasingly applied to monitor ecosystems, regulate visitor flows, and strengthen environmental awareness (Bahou et al., 2024; Lee & Jan, 2023; Pinho & Leal, 2024). These technologies show significant potential for aligning tourism development with conservation objectives while enhancing visitor engagement (Gong & Cao, 2024; Li & Jiang, 2023; Sgroi & Modica, 2024).

Nevertheless, challenges remain. The effectiveness of digital tools varies depending on geographical, infrastructural, and socioeconomic conditions. While some regions have successfully implemented GIS and AR for conservation planning and carrying capacity analysis, others face barriers such as limited internet access, insufficient digital infrastructure, and weak stakeholder collaboration (Aminu et al., 2013; Aminu et al., 2014; Zhao et al., 2020). Similarly, AI and AR/VR applications have been effective for visitor education and interpretation, yet concerns persist about their scalability, cost-effectiveness, and long-term sustainability outcomes (Baldeón et al., 2023, 2024; Chatzopoulou, 2024; Drouga & Sarantakou, 2024).

Despite these contributions, research in this area remains fragmented. Many studies explore individual technologies through isolated case studies without considering their integration, contextual constraints, or long-term impacts (Aminu et al., 2013; Aminu et al., 2014; Erfani et al., 2015; Tan et al., 2018; Sharma & Sehrawat, 2019). There is still limited synthesis explaining how digital innovations collectively advance sustainability objectives in nature-based destinations, or under what conditions they succeed and fail. However, recent research has begun to address this gap, including the work of Parra-Sanchez and Viviescas-Jaimes (2024), which

highlights the emergence of a growing line of inquiry into the role of digital technologies in nature-based tourism.

In response, this paper analyses the role of digital technologies in advancing sustainable nature-based tourism and identifies the key challenges and opportunities associated with their implementation. The central research questions guiding this study are: (1) How do digital technologies contribute to sustainable management and visitor engagement in nature-based tourism? (2) What are the limitations and future directions for their integration in ecologically sensitive destinations? To address these questions, we conduct a systematic literature review of empirical studies applying GIS, DSS, AI, AR/VR, and blockchain. The review highlights best practices, identifies critical gaps in current research, and proposes directions for future technological innovation aligned with environmental, social, and economic sustainability.

The remainder of the paper is organised into five sections: the second section presents the theoretical background, the third section outlines the methodology, the fourth section reports the results, the fifth section discusses key findings, and the sixth section concludes with limitations and directions for future research.

Theoretical Background

Digital transformation has reshaped multiple industries, including tourism, by integrating advanced technologies that optimise management processes, enhance visitor experiences, and contribute to sustainability. In nature-based tourism, digital tools have improved resource conservation, facilitated decision-making, and supported local communities through data-driven strategies. The adoption of technologies such as GIS, DSS, AI and AR/VR has proven to be particularly relevant in promoting sustainable practices in natural environments, while addressing environmental and socioeconomic challenges (Costantino et al., 2024; Sgroi & Modica, 2024). Although the contributions of these technologies are well documented, important questions remain underexplored, particularly regarding their scalability, governance, and long-term impact.

The role of GIS and DSS in sustainable nature-based tourism has been widely documented, particularly in their ability to support spatial planning and environmental monitoring. By analysing geospatial data, these tools assist in identifying suitable areas for tourism development while minimising ecological disruption. Studies conducted in protected areas and natural parks have demonstrated that GIS-based decision models enable authorities to regulate tourism flows, prevent overexploitation of sensitive ecosystems, and design conservation strategies tailored to specific environmental conditions (Aminu et al., 2013; Aminu et al., 2014). Likewise, DSS applications have been employed to integrate ecological, social, and economic factors into tourism planning, ensuring a balanced approach between growth and sustainability in nature-based destinations (Gong & Cao, 2024). Yet, much of this evidence is context-specific, focusing on local or regional applications without addressing questions of scalability or transferability across governance systems. Furthermore, the literature rarely engages with the institutional and political barriers that determine whether these tools are successfully implemented.

In addition to geospatial technologies, applications of AI range from automated visitor management systems in protected areas to predictive analytics for environmental impact assessment. By processing large volumes of data in real time, AI enables personalised recommendations, dynamic pricing strategies, and intelligent monitoring of tourist activities in ecologically sensitive settings (Bahou et al., 2024; Gong & Cao, 2024). However, despite these advantages, implementation of AI often faces challenges related to data availability, technical expertise, and ethical concerns regarding privacy and algorithmic transparency (Baldeón et al., 2023). Beyond these practical obstacles, there is no consensus in the literature about the long-term role of AI in sustainable tourism. While some studies emphasise its transformative potential, others highlight doubts about affordability and inclusivity in resource-constrained regions. This ongoing debate suggests that critical questions remain about AI's scalability and its alignment with sustainability goals.

Another significant strand of research addresses the use of AR/VR in nature-based tourism. These technologies have been leveraged to create immersive educational experiences that promote environmental awareness and cultural heritage preservation in natural settings. In practice, AR applications allow tourists to explore landscapes through interactive digital overlays, providing contextual information without physically altering the environment (Jomsri, 2019; Martínez-Graña et al., 2023; Sancho-Jiménez et al., 2024; Mohd Rafee et al., 2024; Methimakis et al., 2024). Virtual reality has also been used to develop remote tours of ecologically sensitive areas, enabling access while reducing human impact on fragile ecosystems (Chatzopoulou, 2024; Triviño-Tarradas et al., 2024). Despite these benefits, widespread adoption remains limited due to high implementation costs and infrastructure constraints, particularly in remote or underdeveloped natural areas (Baldeón et al., 2024). More importantly, the literature tends to emphasise experiential and educational benefits while overlooking critical issues such as accessibility, cultural sensitivity, and the risk of 'virtual overexposure' of fragile environments. This under-engagement with potential unintended consequences points to a gap in the theoretical discussion of AR/VR within sustainable tourism research.

While digital transformation presents numerous opportunities for sustainable nature-based tourism, it also raises significant challenges. Technological accessibility is a major barrier, as many destinations lack the infrastructure to support digital innovations. Limited internet connectivity, inadequate hardware, and high implementation costs hinder adoption in natural contexts, particularly in developing regions (Drouga & Sarantakou, 2024; Zhao et al., 2020). Additionally, rapid digitalisation raises ethical and social concerns, including digital exclusion and the commodification of cultural and ecological heritage. Without proper governance frameworks, there is a risk that digital initiatives may disproportionately benefit large corporations while marginalising local communities (Van et al., 2020).

A further challenge is the overexposure of natural destinations due to digital marketing and online platforms: increased visibility of remote and ecologi-

cally sensitive locations can drive unsustainable mass tourism, exceeding carrying capacity and threatening biodiversity (Li & Jiang, 2023). In some cases, AR applications and AI-driven recommendations have contributed to overcrowding in fragile ecosystems, underscoring the risk of unintended negative consequences (Mohd Rafee et al., 2024). Addressing these issues requires sustainable digital strategies that balance technological innovation with responsible practice; yet the literature seldom examines how governance frameworks, community participation, or regulatory mechanisms can mitigate these effects, leaving an important avenue for future research.

Despite these challenges, digital transformation remains a key driver of sustainability in nature-based tourism. The integration of technologies such as GIS, DSS, AI, and immersive tools like AR/VR provides valuable support for conservation efforts, visitor management, and community engagement in natural areas. The relationship between digital technologies, tourism management, and sustainability in nature-based contexts is inherently complex and interconnected. Digital technologies (GIS and DSS) play a crucial role in spatial planning and environmental monitoring, enabling authorities to identify suitable areas for tourism development while minimising ecological disruption. Artificial intelligence enhances real-time decision-making, predictive analysis, and personalised visitor experiences (Samala et al., 2022), while AR/VR facilitates immersive educational encounters that foster environmental awareness without physically altering natural environments (Han et al. 2019). The Internet of Things (IoT) also contributes by enabling real-time data collection on visitor behaviour and environmental conditions (Baldeón et al., 2024). These tools offer opportunities for proactive management, but studies have yet to explore how IoT can be effectively integrated with other technologies or what governance frameworks are needed to regulate data ownership, privacy, and interoperability; without this discussion, IoT remains under-theorised in the tourism literature.

Collectively, these technologies optimise resource allocation, improve operational efficiency, and support inclusive, data-driven strategies in nature-based

tourism. In turn, effective tourism management contributes to broader sustainability goals by promoting environmental protection, economic development, and social well-being. Yet the current literature often privileges technical descriptions over critical reflection. There is still limited engagement with questions of governance, power asymmetries, or the distributive impacts of digitalisation in natural destinations. Addressing these blind spots requires moving beyond cataloguing technologies to examine how they interact with institutional frameworks, cultural contexts, and ethical concerns. Future research should therefore not only explore hybrid models that integrate multiple technologies (Chatzopoulou, 2024; Sancho-Jiménez et al., 2024), but also engage with broader theoretical debates on equity, inclusion, and long-term sustainability in digital tourism.

Methodology

This study adopts a systematic literature review (SLR) to evaluate the role of digital technologies in advancing sustainable nature-based tourism. The SLR method was selected because it ensures methodological transparency, reproducibility, and analytical depth while enabling a comprehensive synthesis of existing knowledge (Watson & Webster, 2020; Webster & Watson, 2002). Through the structured analysis of diverse case studies and regional experiences, this approach allows the identification of emerging patterns, theoretical contributions, and research gaps relevant to the digital transformation of tourism practices in natural environments such as national parks, protected areas, and ecotourism destinations (Gong & Cao, 2024; Neumann & Mason, 2023; Vasconez & Weber, 2023).

The review is grounded in the methodological principles proposed by Webster and Watson (2002), who advocate for a concept-centric rather than author-centric approach. Instead of merely summarising prior studies by author or chronology, the concept-centric method organises findings around key thematic constructs. In the context of nature-based tourism, this means identifying how specific digital technologies – such as GIS, AI, DSS, and AR/VR – contribute to functions like spatial zoning, biodiversity conservation, visitor education, and real-time envi-

ronmental monitoring. This orientation allows for a higher-level synthesis that reveals the relationships among core concepts, technologies, and sustainability outcomes – essential for understanding the complex and interdisciplinary nature of digital transformation in natural tourism contexts.

Moreover, the updated roadmap proposed by Watson and Webster (2020) reinforces the need for literature reviews to move beyond descriptive aggregation and toward the development of theoretical insights. They suggest that literature reviews should act as bridges between past research and future theorising, combining rigorous synthesis with conceptual modelling. By applying these methodological standards, this study ensures the inclusion of high-quality, peer-reviewed academic sources. The reviewed works were drawn from indexed journals and conference proceedings in fields such as tourism management, information systems, environmental studies, and sustainability science. Studies focused on cultural, urban, or non-nature-based tourism settings, grey literature, and non-peer-reviewed sources were excluded to ensure relevance and analytical rigour.

To ensure methodological coherence and analytical depth, the systematic literature review was carried out in three structured phases, presented in the following subsections:

1. The collection and selection of relevant academic articles.
2. The classification and detailed analysis of the extracted information.
3. The synthesis of findings with the identification of conceptual and technological trends related to sustainable nature-based tourism.

Data Collection and Article Selection

The literature search was conducted using a database containing 226 academic articles related to tourism, digitalisation, and sustainability. Following the structured approach recommended by Watson and Webster (2020), a systematic identification, classification, and synthesis process was applied to ensure rigour and replicability. A structured search strategy was implemented, using a combination of keywords

and Boolean operators to ensure precision and relevance. The search terms focused on two core dimensions: (1) nature-based tourism, and (2) digital technologies.

For the nature-based tourism dimension, the search included the following terms in titles, abstracts, and keywords: ‘nature-based tourism’, ‘nature tourism’, ‘ecotourism’, ‘sustainable tourism’, ‘wildlife tourism’, ‘outdoor tourism’, ‘adventure tourism’, and ‘rural tourism’. These terms were selected to encompass the range of tourism activities associated with natural environments, biodiversity, and outdoor experiences.

For the digital technologies dimension, the search included: ‘digital technology’, ‘artificial intelligence’, ‘augmented reality’, ‘geographic information systems’, and ‘decision support systems’, with the aim of identifying studies that explore how these tools are applied in tourism planning, visitor experience design, and conservation strategies. Boolean operators (AND, OR) were used to combine terms, ensuring that both thematic axes were captured in the review process.

To ensure the inclusion of high-quality and relevant studies, specific selection criteria were applied. Articles were considered for analysis if they presented empirical applications of digital technologies in nature-based tourism destinations – such as national parks, ecotourism sites, protected areas, or rural communities – and examined the role of technologies like artificial intelligence, augmented reality, geographic information systems, decision support systems, blockchain, and the Internet of Things. Preference was given to studies that included sustainability-related outcomes, such as environmental impact mitigation, resource optimisation, biodiversity protection, or community engagement.

In parallel, exclusion criteria were applied to maintain analytical rigour. Studies that were purely theoretical or lacked empirical evidence were excluded, as were those that did not address nature-based tourism contexts. Articles that focused exclusively on digital marketing without a clear sustainability or conservation component were also omitted. After applying these criteria, 50 articles were retained for full-text analysis, forming the basis for the systematic review. Although not all articles are explicitly cited

in the text, each contributed to the overall synthesis of findings and conceptual categorisation relevant to the digital transformation of sustainable nature-based tourism.

Classification and Analysis of Information

The selected articles were systematically reviewed and categorised to facilitate comparison. A structured classification system was used to organise the studies based on their objectives, methodologies, and key findings. Each article was analysed according to specific dimensions, including the nature-based tourism context, geographical scope, technological solutions implemented, research methodology, and findings.

The study context dimension focused on defining the research problem, objectives, and the relevance of each study within the field of sustainable nature-based tourism, emphasising challenges such as conservation, visitor pressure, or community inclusion in natural destinations. The geographical scope included information about the study location, its environmental characteristics (e.g. protected areas, national parks, coastal or mountainous ecosystems), and cultural or ecological factors influencing tourism in natural settings. The technological solutions dimension described the digital tools applied in each case – such as GIS, AI, AR, or the Internet of Things – and their functionalities in addressing key sustainability concerns in nature-based tourism. The research methodology dimension examined the approaches used for data collection, validation techniques, and analytical frameworks employed in assessing technological impacts. Lastly, the findings dimension summarised the key results and their implications for the sustainability of tourism in natural environments, including insights on environmental monitoring, visitor education, and ecosystem protection.

Synthesis of Findings and Identification of Trends

Following data classification, the extracted information was synthesised to identify patterns and insights. The synthesis process involved grouping studies according to the type of digital technology implemented and evaluating their impact on sustainable nature-based tourism. This thematic approach fo-

cused on the role of digital technologies in supporting conservation efforts, improving visitor experiences, and promoting responsible tourism in natural environments. It allowed for a structured presentation of findings, distinguishing between GIS-based spatial planning tools used in protected areas, AI-driven visitor management systems implemented in ecotourism sites, AR/VR applications designed to enhance environmental education, and IoT-based systems for real-time environmental monitoring in nature reserves.

The synthesis of findings is presented in Section 4, where the impact of each digital technology is analysed based on regional applications, case studies, and sustainability outcomes in nature-based tourism contexts. This includes evaluations of how digital tools contribute to biodiversity conservation, help mitigate overcrowding in ecologically fragile areas and support local communities through data-driven management strategies.

Results

This section presents the main findings of the systematic literature review, focusing on the application of digital technologies in sustainable nature-based tourism. The studies analysed reveal how tools such as GIS, DSS, AI, AR/VR, and predictive modelling are being implemented in diverse ecological contexts, including protected areas, coastal zones, wetlands, and national parks. Each subsection highlights the specific contributions of these technologies to improving environmental conservation, enhancing visitor management, and fostering educational and immersive experiences, while also addressing the challenges and limitations encountered in their application.

Geographic Information Systems and Decision Support Systems

GIS and DSS have played a crucial role in spatial decision-making for sustainable nature-based tourism planning, particularly in the management of protected areas, wetlands, and coastal ecosystems. In Malaysia, a GIS-based DSS was implemented to classify conservation zones while optimising tourism development. A study conducted in the Johor Ramsar sites applied Spatial Decision Support Systems (SDSS) to ensure that tourism activities did not disrupt ecologically sensi-

tive wetlands, resulting in improved conservation outcomes and regulated visitor access (Aminu et al., 2013).

Similarly, in Taiwan, an integrated coastal zone management model using GIS was employed to assess the impact of tourism on marine biodiversity in the Kaohsiung region. This system enabled local authorities to identify high-risk areas for pollution and overcrowding, which led to the implementation of new regulations that helped reduce environmental degradation in coastal nature-based tourism destinations (Aminu et al., 2013).

In Iran's Zabol region, the application of GIS-based multi-criteria analysis has also proven significant. Here, DSS tools were used to zone tourism areas according to ecological and socioeconomic indicators, ensuring a balance between tourism-driven economic growth and the conservation of natural landscapes (Gong & Cao, 2024). These case studies demonstrate the strategic value of GIS and DSS in advancing sustainable nature-based tourism by enabling informed spatial planning, environmental risk assessment, and visitor flow regulation.

Artificial Intelligence and Automation

Artificial Intelligence has increasingly transformed the management of nature-based tourism, particularly in visitor flow regulation, real-time monitoring, and personalised experiences in protected natural areas. In China, AI-powered models have been used to predict tourism demand trends, enabling authorities to regulate visitor flows in ecologically sensitive attractions. A notable example is the Jiuzhaigou Valley, a UNESCO World Heritage Site and national park, where machine learning algorithms were employed to optimise tourist distribution across the site, preventing overcrowding while enhancing visitor satisfaction and reducing pressure on fragile ecosystems (Bahou et al., 2024).

In Vietnam, AI-powered Human-Machine Interaction (HMI) devices have contributed to the recovery and regulation of nature tourism in the post-pandemic context. These systems provided real-time health and safety information and helped manage visitor density in popular natural destinations, ensuring a safe and personalised experience while minimising environmental impact (Van et al., 2020).

Additionally, in Saudi Arabia, although not exclusively focused on nature-based tourism, the integration of AI with blockchain technology has improved transaction transparency in tourism services. This development is particularly relevant for eco-lodges and rural tourism operators seeking to build trust with international visitors through secure and traceable systems (Gong & Cao, 2024). Overall, AI and automation have demonstrated strong potential for supporting the sustainable management of natural tourism areas. AI also enables smart decision-making in areas such as carrying capacity management, emergency response, and dynamic pricing strategies tailored to environmental conservation goals.

Augmented Reality and Virtual Reality

Augmented and Virtual Reality technologies have shown considerable potential in nature-based tourism, particularly by enhancing environmental education and reducing the physical impact of tourism infrastructure. In Peru, AR-based ecotourism trails have been developed in Amazonian reserves, where Bluetooth beacons and mobile AR applications deliver immersive storytelling experiences about local biodiversity and ecosystems. These solutions eliminate the need for intrusive signage or built structures, preserving the integrity of the natural environment while enriching the visitor experience (Baldeón et al., 2024).

In Greece, underwater AR solutions have transformed marine heritage tourism by enabling visitors to virtually explore submerged archaeological sites without disturbing delicate aquatic ecosystems. This approach not only fosters awareness of underwater cultural heritage but also promotes responsible tourism practices that reduce direct human interference in vulnerable environments (Chatzopoulou, 2024).

A comparable strategy has been implemented in Spain through AR and VR applications along geotourism routes in Monsagro, Salamanca. These digital tools provide real-time geological interpretation, allowing visitors to learn about the region's natural history without the need for physical installations that might affect the landscape (Liao et al., 2013).

In sum, AR and VR technologies are powerful tools for advancing sustainable nature-based tourism. By enabling immersive, low-impact, and accessible experiences, these technologies help reconcile environmental conservation with educational and interpretive goals. Their application contributes to the protection of natural and cultural heritage by minimising the physical footprint while deepening visitor engagement with the unique values of natural destinations.

Predictive Modelling for Nature-Based Tourism Management

The use of predictive modelling as a valuable tool for managing visitor flows and mitigating environmental impacts in nature-based tourism settings has been examined in the works of Baldeón et al. (2023) and Bahou et al. (2024). Although primarily applied in urban contexts, approaches like the dynamic system models used in Amsterdam also offer useful insights for natu-

ral destinations. These models simulate various tourism management scenarios and can be adapted to nature-based tourism areas to guide decision-makers in planning strategies that balance visitor demand with conservation priorities (Baldeón et al., 2023).

In China, machine learning models have been used to forecast visitor numbers at ecologically sensitive sites such as national parks and nature reserves. These models assist authorities in regulating carrying capacity and implementing crowd control measures, helping to prevent ecosystem degradation while maintaining quality visitor experiences (Bahou et al., 2024).

Predictive modelling, particularly when powered by AI and real-time data, represents a promising path for proactive planning in protected areas, enabling authorities to anticipate environmental pressures and design interventions that ensure the long-term sustainability of tourism in natural environments.

Table 1 Comparison of Digital Technologies in Sustainable Nature-Based Tourism

Technology	Main Benefits	Challenges	Key Applications
Artificial Intelligence	Personalised visitor experiences, predictive analytics for tourism flows.	Data privacy concerns, high implementation and maintenance costs.	Chatbots, smart recommendations, demand forecasting, congestion management.
Geographic Information Systems	Spatial planning, mapping of sensitive areas, environmental monitoring.	Requires high-quality and up-to-date geospatial data.	Zoning protected areas, analysing tourism impact, supporting conservation planning.
Decision Support Systems	Integrated decision-making, multi-criteria sustainability assessments.	Difficulty integrating diverse and complex datasets.	Tourism development planning, conservation trade-off modelling.
Augmented & Virtual Reality	Immersive environmental education, reduced physical impact on fragile sites.	High infrastructure and equipment costs, limited scalability.	Interactive nature trails, virtual exploration of remote or sensitive ecosystems.
Big Data	Trend identification, behaviour analysis, evidence-based tourism management.	Requires robust data processing and storage infrastructure.	Visitor behaviour analytics, sustainability performance tracking.
Internet of Things	Real-time monitoring of environmental conditions, automation of tourism services.	Dependence on connectivity, device maintenance and calibration.	Monitoring air and water quality, wildlife tracking, visitor density management.

Note Table 1 summarises digital technologies applied to sustainable nature-based tourism. Categories include main benefits, associated challenges, and key applications in tourism contexts. Technologies are organised by type and listed alphabetically. Abbreviations used are consistent with those in the main text. No numerical units are presented, as the content is qualitative.

Comparative Analysis of Digital Technologies in Sustainable Nature-Based Tourism

The comparative analysis of the literature reveals that the effectiveness of digital technologies in nature-based tourism depends greatly on their intended function and the ecological context in which they

are applied. Rather than offering a universal solution, each technological approach contributes in distinct ways to the planning, management, and sustainability of natural destinations.

Spatial technologies such as geographic information systems and decision support systems are par-

Table 2 Categorisation of Reviewed Studies by Technology Type

Technology Category	Description of Category	Citations
Extended Reality (XR)	VR, AR, 3D modelling, holograms.	Liao et al. (2013), Aminu et al. (2014), Nobnop et al. (2018), Baldeón et al. (2023), Baldeón et al. (2024), Costantino et al. (2024), Sgroi and Modica (2024), Wang and Zhang (2025), Baldeón et al. (2025), Nuraini et al. (2025)
Artificial Intelligence and Big Data	Machine Learning, AI for personalisation, trend prediction.	Wasserburger et al. (2017), Jomsri (2019), Wang (2020), Van et al. (2020), Vasconez and Weber (2023), Huang (2023), Mohd Rafee et al. (2024), Sancho-Jiménez et al. (2024), Louati et al. (2024), Bahou et al. (2024), Zhang and Cheng (2024), Noviarita et al. (2024), Methimakis et al. (2024), Triviño-Tarradas et al. (2024), Ma et al. (2024), Chengcai et al. (2024), Kusumastuti et al. (2024)
IoT and Sensors	Environmental sensors, smart navigation, wearable devices.	Aminu et al. (2013), Sharma and Sehrawat (2019), Şakar et al. (2020), Li and Jiang (2023), Kashem et al. (2023), Chatzopoulou (2024), Huang et al. (2024), Velasco et al. (2024), Cheng et al. (2024), Lu (2024), Baldeón et al. (2025)
Blockchain and Cyber-security	Cryptocurrency, tourism traceability, secure bookings.	Erfani et al. (2015), Tan et al. (2018), Lv et al. (2021), Drouga and Sarantakou (2024), Kim et al. (2024).
Digital Platforms and Mobile Apps	Tourism apps, chatbots, e-commerce.	Aminu et al. (2014), Erfani et al. (2015), Martínez-Graña et al. (2017), Tan et al. (2018), Van et al. (2020), Huang (2023), Baldeón et al. (2023), Martínez-Graña et al. (2023), Neumann and Mason (2023), Sancho-Jiménez et al. (2024), Chiwaridzo and Chiwaridzo (2024), Bahou et al. (2024), Pinho and Leal (2024), Kusumastuti et al. (2024), Nuraini et al. (2025), Baldeón et al. (2025)
Geolocation and Digital Mapping	Interactive maps, geo-routes, GPS in tourism.	Sharma and Sehrawat (2019), Chatzopoulou (2024), Zhang and Cheng (2024), Huang et al. (2024), Liu et al. (2024), Cheng et al. (2024)
Management Systems and Smart Cities	Impact analysis, tourist flow monitoring.	Li and Jiang (2023), Neumann and Mason (2023), Bahou et al. (2024)
Interactive Experiences and Gamification	Digital games, immersive tourism, metaverse.	Liao et al. (2013), Aminu et al. (2014), Martínez-Graña et al. (2017), Nobnop et al. (2018), Zhao et al. (2020), Baldeón et al. (2023), Martínez-Graña et al. (2023), Gong and Cao (2024), Huang et al. (2024), Cheng et al. (2024)
Accessible Tourism and Inclusive Technologies	Voice recognition apps, digital adaptations.	Aminu et al. (2014), Martínez-Graña et al. (2017), Nobnop et al. (2018), Zhao et al. (2020), Van et al. (2020), Baldeón et al. (2023)

Note Table 2 categorises the reviewed studies based on the type of digital technology applied in tourism contexts. Each category includes a description of the technologies involved and corresponding citations. The technologies are listed by thematic relevance rather than alphabetically. Abbreviations and terminology are consistent with those used in the main text. Citations reflect the body of literature analysed in the review.

ticularly valuable for informing land-use planning, conservation zoning, and biodiversity monitoring in protected areas, wetlands, and coastal zones. Their strength lies in enabling data-driven decisions that align tourism development with environmental thresholds and conservation objectives.

Meanwhile, augmented reality and virtual reality technologies have demonstrated considerable potential in delivering immersive, low-impact educational experiences. By offering interpretive content through digital overlays or virtual simulations, these tools foster environmental awareness without the need for intrusive infrastructure, making them especially suitable for ecotourism, geotourism, and marine heritage sites.

As summarised in Table 1, each digital technology presents specific advantages, limitations, and areas of application within sustainable nature-based tourism. The table provides a comparative overview that facilitates a better understanding of how these technologies support diverse aspects of destination management – from spatial analysis and predictive planning to visitor education and environmental protection. Aligning technological choices with site-specific conservation and community priorities emerges as a critical factor for achieving long-term sustainability outcomes.

This study incorporates a complementary classification that maps all 50 reviewed articles according to the primary categories of digital technologies they address. Table 2 presents this categorisation, grouping the sources into nine key technological domains identified throughout the systematic review: extended reality; artificial intelligence and big data; IoT and sensors; blockchain and cybersecurity; digital platforms and mobile applications; geolocation and digital mapping; management systems and smart cities; interactive experiences and gamification; and accessible tourism and inclusive technologies.

The table serves a dual purpose: first, to offer a clearer visual representation of the distribution and diversity of digital innovations applied in sustainable nature-based tourism; and second, to ensure proper attribution of all studies included in the analytical process – even those not explicitly cited in the main text – thus reinforcing the methodological rigour and transparency of the review.

As Table 2 illustrates, artificial intelligence and big data emerge as the most widely represented technological category among the reviewed studies, reflecting their growing influence in predictive analytics, personalised tourism services, and visitor flow management. Extended reality technologies, including augmented and virtual reality, also show a significant presence, particularly in applications related to environmental education and immersive heritage experiences.

Categories such as IoT and sensors, and digital platforms and mobile apps demonstrate the increasing integration of real-time monitoring tools and user-centric applications in nature-based destinations. Meanwhile, areas like blockchain and accessible tourism appear less frequently in the literature, suggesting promising but underexplored fields for future research.

Overall, this classification not only highlights the technological breadth of the field but also identifies areas with concentrated scholarly interest and potential research gaps. It contributes to a deeper understanding of how digital innovation is currently shaping – and could further enhance – the sustainable development of tourism in natural environments.

Discussion

Emerging Trends and Persistent Challenges in Nature-Based Tourism

Despite the growing potential of digital technologies to support sustainability in nature-based tourism, several barriers continue to hinder their large-scale and equitable adoption. These challenges go beyond technological limitations and encompass economic, social, and political dimensions that are particularly pronounced in ecologically sensitive and remote destinations.

Economic barriers are among the most pressing. Many nature-dependent tourism regions – especially in the Global South – lack the financial resources to invest in robust digital infrastructures, such as 5G networks, AI-powered data systems, and AR/VR equipment. For example, a study on rural tourism in Malaysia revealed that high initial investment costs discouraged local businesses from adopting smart

solutions, despite recognizing their long-term benefits (Mohd Rafee et al., 2024). Similar patterns are observed in Africa and Latin America, where the high cost of GIS-based has restricted their deployment in conservation areas (Aminu et al., 2013).

Social barriers also limit digital transformation. In several cases, resistance from traditional tourism actors – such as local guides or small-scale operators – has emerged due to concerns over job displacement and loss of cultural authenticity. In Vietnam, tour guides feared that AI-based assistants might replace human interaction, even though these tools improved visitor personalisation (Van et al., 2020). Likewise, in Saudi Arabia, blockchain-based transaction systems faced scepticism and low adoption rates due to a lack of awareness and regulatory clarity (Gong & Cao, 2024).

Political and regulatory barriers further complicate the integration of digital tools in protected and rural tourism destinations. In China, while AI-driven models significantly reduced congestion in major tourist attractions, the absence of unified national regulations for AI has limited the scalability of these initiatives (Bahou et al., 2024). In Europe, concerns related to data protection laws (e.g. General Data Protection Regulation) have slowed the implementation of AI-driven visitor tracking systems, which could otherwise optimise flows in ecologically sensitive zones (Aminu et al., 2013).

Technological barriers are also notable. The rapid pace of innovation often renders tools obsolete within a few years, posing long-term sustainability challenges. For instance, a case study in Spain found that AR applications implemented in a nature-based tourism project became outdated within five years due to hardware and software incompatibilities, leading to costly upgrades (Liao et al., 2013).

Lessons from Failed or Limited Implementation Cases

Analysing unsuccessful or limited-impact implementations provides critical insights for designing future digital strategies in nature-based tourism. In Taiwan, a GIS-supported coastal tourism management initiative failed to achieve its goals due to insufficient stake-

holder engagement. This highlighted the importance of coupling technological interventions with inclusive governance and participatory planning processes (Aminu et al., 2014). In Amsterdam, a system dynamics model aimed at forecasting visitor behaviour in urban parks was unsuccessful in accurately capturing real-time tourist dynamics, revealing the limitations of static computational models without adaptive mechanisms (Baldeón et al., 2023). Similarly, in Iran, a DSS-based tourism zoning project failed to reconcile ecological priorities with economic development because it lacked meaningful community consultation, leading to local resistance and implementation gaps (Gong & Cao, 2024).

Practical and Theoretical Implications

From a practical perspective, this review emphasises the need to align digital innovation with the local realities of nature-based tourism destinations. Technological solutions must be supported by adequate infrastructure, institutional capacity, and participatory governance. The success of hybrid models that integrate GIS, AI, AR/VR, and DSS depends not only on technical design but also on the involvement of local communities, especially in biodiversity-rich areas where livelihoods are closely tied to natural resources.

From a theoretical standpoint, the findings contribute to advancing the conceptual framework of smart sustainable tourism by demonstrating that digital transformation in nature-based tourism cannot be divorced from context. The evidence suggests that integrated models are more effective when embedded in place-based approaches that recognise ecological vulnerability, cultural values, and governance complexity. Future research should explore context-sensitive frameworks that evaluate digital innovation not just by efficiency gains, but by their contributions to ecological resilience, equity, and cultural preservation.

Conclusions

This study demonstrates that digital technologies play a pivotal role in enhancing the sustainability of nature-based tourism, particularly by supporting resource management, improving visitor experienc-

es, and contributing to environmental conservation. Tools such as GIS, DSS, AI, AR/VR, and predictive modelling have enabled more informed decision-making in the planning and management of protected areas, ecotourism sites, and biodiversity-rich landscapes. Their implementation facilitates spatial zoning, visitor flow regulation, immersive education, and early detection of environmental pressures – functions that are essential in ecologically sensitive contexts.

However, despite these promising contributions, significant challenges remain. Infrastructure limitations, lack of digital literacy, regulatory gaps, and socio-cultural resistance to technological change continue to hinder the widespread adoption of digital tools, especially in developing regions. Overcoming these barriers requires strategic investment in digital infrastructure, the formulation of clear regulatory frameworks that ensure ethical data governance and equitable access, and the active involvement of local communities in the design and implementation of technological solutions.

For policymakers, these findings underscore the importance of integrating digital innovation into sustainable development agendas. Public-private partnerships should be promoted to deploy AI-driven analytics, GIS-based conservation planning, and immersive AR/VR tools tailored to natural destinations. Regulatory frameworks must also adapt to address the risks and opportunities of rapidly evolving technologies, ensuring that innovation aligns with ecological sustainability and social inclusion.

From an industry perspective, the next phase involves scaling successful hybrid technology models and fostering cross-sector collaboration. Tourism operators in nature-based destinations should focus on implementing intelligent visitor management systems, developing interpretive AR/VR experiences that minimise the ecological footprint, and exploring secure technologies such as blockchain to enhance transparency and trust in eco-tourism transactions. Workforce development through targeted training is also essential to build the technical capacity required to operate and maintain these tools effectively.

Theoretically, this study contributes to a more nuanced understanding of how digital transformation

interacts with the unique dynamics of nature-based tourism. It highlights the need to move beyond isolated technological interventions and toward integrative frameworks that combine spatial, predictive, and immersive technologies within governance systems that respect ecological limits and local knowledge.

Future research should investigate the long-term impacts of digital technologies on sustainability outcomes, particularly in relation to biodiversity conservation, carbon reduction, and community resilience. More empirical studies are needed to assess how regulatory interventions influence the effectiveness of digital solutions in rural and protected areas. In addition, the potential of hybrid models – combining GIS, AI, AR/VR, and IoT – remains underexplored and offers a rich avenue for investigation, especially in data-scarce and infrastructure-limited regions across Latin America, Africa, and Southeast Asia.

Lastly, as digitalisation in tourism accelerates, ethical considerations must be placed at the centre of innovation. Issues such as data privacy, algorithmic transparency, and digital inclusion require robust governance mechanisms to ensure that digital transformation in nature-based tourism is not only efficient, but also equitable and responsible.

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