

REVIEW ARTICLE

Artificial intelligence and Tourism 4.0 for sustainable transformation: A systematic review of environmental and governance impacts

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Abstract

Artificial intelligence (AI) and the concept of Tourism 4.0 have transformative potential in advancing sustainable tourism, particularly in addressing environmental and governance challenges. This systematic literature review, conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses 2020 guidelines, compiles peer-reviewed studies from 2015 to 2023 to evaluate AI's role within Tourism 4.0 in promoting sustainability. The analysis focuses on two domains: Environmental impacts, such as energy efficiency, resource conservation, and low-carbon tourism strategies, and governance impacts, including transparent certification, accountable digital platforms, and data-driven policy innovation. While AI and related smart systems demonstrate positive outcomes, critical issues, such as cost barriers, data privacy concerns, and limited long-term evaluation, remain underexplored. The review also highlights research gaps, including the scarcity of integrated frameworks and longitudinal studies. Building on these findings, recommendations for Malaysia emphasize strengthening smart infrastructure, piloting blockchain-based transparency systems, enhancing institutional coordination, and embedding energy-efficient AI solutions into governance frameworks. By situating Malaysia at a mid-evolution stage of digital tourism, the study offers practical insights into how AI and Tourism 4.0 can support environmentally sustainable and ethically governed tourism futures.

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1. Introduction

During the Fourth Industrial Revolution, the tourism industry has experienced a significant transformation with the advent of Tourism 4.0. Characterized by the integration of the latest digital technologies, such as artificial intelligence (AI), the Internet of Things (IoT), big data analytics, virtual reality (VR), and blockchain, Industry 4.0 is revolutionizing traditional paradigms in most sectors, including tourism.¹ This development has given rise to the concept of Tourism 4.0, which seeks to utilize these innovations to enhance tourist experiences, optimize operational efficiencies, and advance sustainable practices in the tourism sector.²

Tourism 4.0 is not merely the adoption of technology but a holistic concept that integrates stakeholders from tourists and service providers to governments and local communities into a collaborative system.^{3,4} With the utilization of real-time data and smart systems, destinations can offer personalized experiences, manage their resources more effectively, and mitigate the adverse impacts of mass tourism. For instance, IoT devices can monitor tourist flows to prevent overcrowding, and AI-driven platforms can provide personalized recommendations, both of which can enhance visitor satisfaction and promote equitable distribution of tourism benefits.⁴

Sustainable development, as framed by the United Nations' Sustainable Development Goals, provides a wider context for understanding the role of digital technologies in tourism.⁵ New Industry 4.0 technologies, such as AI, IoT, blockchain, and augmented reality (AR)/VR, affect the functioning of tourism enterprises by reshaping energy management, transparency, and customer engagement in ways that align with sustainability principles. For example, AI and IoT enable resource efficiency and lower emissions; blockchain provides transparent supply chains and certification systems; and AR/VR offer low-impact tourism alternatives.⁶ These technologies demonstrate how Industry 4.0 is not only a driver of competitiveness but also a key facilitator of sustainable development. Tourism enterprises increasingly embed these tools into their operations by linking digital transformation with ecological conservation, community empowerment, and responsible governance practices.⁶

Sustainability has become a central principle in contemporary tourism development, especially against the backdrop of phenomena such as climate change, resource depletion, and sociocultural disruption. Tourism 4.0 offers promising solutions to these challenges by facilitating data-driven decision-making, promoting sustainable consumption, and enhancing community engagement.⁷ Recent reviews also highlight that AI is increasingly integrated into sustainability reporting frameworks across industries, supporting transparency, accountability, and responsible governance. This broader trend underscores the relevance of AI applications in tourism governance.^{7,8} However, the application of Industry 4.0 technologies to tourism practices also creates challenges such as data privacy issues, digital divides, and the need for significant infrastructural investments.

This review is relevant because it clarifies how Industry 4.0 technologies contribute to sustainability in tourism at a time when destinations face urgent pressures to recover from the pandemic without reverting to unsustainable mass-tourism models. It contributes to the research area by providing one of the first systematic reviews that explicitly

frames AI within the Tourism 4.0 paradigm, linking environmental and governance outcomes to the broader discourse on sustainable development.

While growing attention has been given to Tourism 4.0, in-depth studies examining the intersection of Industry 4.0 technologies and sustainable tourism development in a systematic manner remain limited. Literature is often focused on either specific technological applications or individual case studies without offering an integrating framework that outlines the grand implications of this digital revolution.⁹ This lack undermines the need for a systematic literature review that consolidates current knowledge, explains prevailing trends, and identifies areas warranting further research and governance.

This systematic review aims to:

- (i) Present a systematic literature review of the application of Industry 4.0 technologies in the tourism sector.
- (ii) Analyze the potential of these technologies to enable sustainable tourism.
- (iii) Identify challenges and opportunities for the implementation of Tourism 4.0 initiatives.
- (iv) Propose an agenda for future research in this multidisciplinary field.

By achieving these objectives, this study can provide a general overview of how Industry 4.0 technologies are revolutionizing the tourism industry, particularly in relation to sustainability. The results may benefit researchers, practitioners, and policymakers seeking to address digital transformation challenges in tourism.

2. Methodology

This systematic literature review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) 2020 guidelines by Page *et al.*¹⁰ that were built on the original PRISMA principles proposed by Moher *et al.*¹¹ A prespecified review protocol outlined the search strategy, inclusion and exclusion criteria, data-extraction procedures, and synthesis steps.

2.1. Data sources

Systematic searches were performed in electronic databases (i.e., Scopus, Web of Science, ScienceDirect) and Google Scholar for articles published between 2015 and 2023 (including early 2024 where available). Reference lists identified during the review process were also screened to supplement the database search. The search strings combined terms related to sustainable tourism and Industry 4.0 technologies (e.g., “sustainable tourism” AND “Industry 4.0” OR “AI” OR “IoT” OR “blockchain” OR “big data” OR “virtual reality”).

Google Scholar was used only to capture additional references and gray literature. To reduce bias, only the first 10 pages of Google Scholar results were reviewed, whereas Scopus, Web of Science, and ScienceDirect served as the primary indexed sources.

2.2. Inclusion and exclusion criteria

This research considered conference papers and peer-reviewed journal articles that explicitly mentioned the use of one or more Industry 4.0 technologies to improve or investigate sustainable tourism outcomes. The research could be empirical or conceptual, but needed to address tourism sustainability (environmental, social/cultural, or economic). Only studies written in the English language were considered. We excluded studies that did not focus on tourism or sustainability (e.g., pure tech development papers without a tourism context), did not address the said technologies, and were unavailable in full text. To ensure recency and relevance, preference was given to research in the recent decade with a global scope.

2.2.1. Screening and selection

After database searches, all records were merged and duplicates removed. Titles and abstracts of unique records were screened for inclusion criteria, and full-text screening was performed for eligible papers. Two independent reviewers conducted screening, with disagreements resolved through consensus. Figure 1 shows the PRISMA flow diagram of study selection.

The search identified 520 records from database searches and additional sources. After duplicate removal ($n = 100$), 420 unique records were screened, of which 350 were excluded for irrelevance. Full-text articles ($n = 70$) were assessed for eligibility, and 20 studies met all inclusion criteria.

2.2.2. Data extraction and synthesis

Study information, such as author/year, target technology, study context/methods, and key findings relating to sustainable tourism, was mapped using a data extraction form. We then performed qualitative thematic synthesis. Initial coding of findings within each study was performed to identify emerging themes or outcome domains. Codes were iteratively refined and grouped into more encompassing thematic categories that reflect how Industry 4.0 technologies enable sustainable tourism. Coding and theme development were checked for consistency by a second reviewer. Study characteristics (Table 1) and thematic findings (Table 2) were tabulated. Finally, we considered overall trends, key findings,

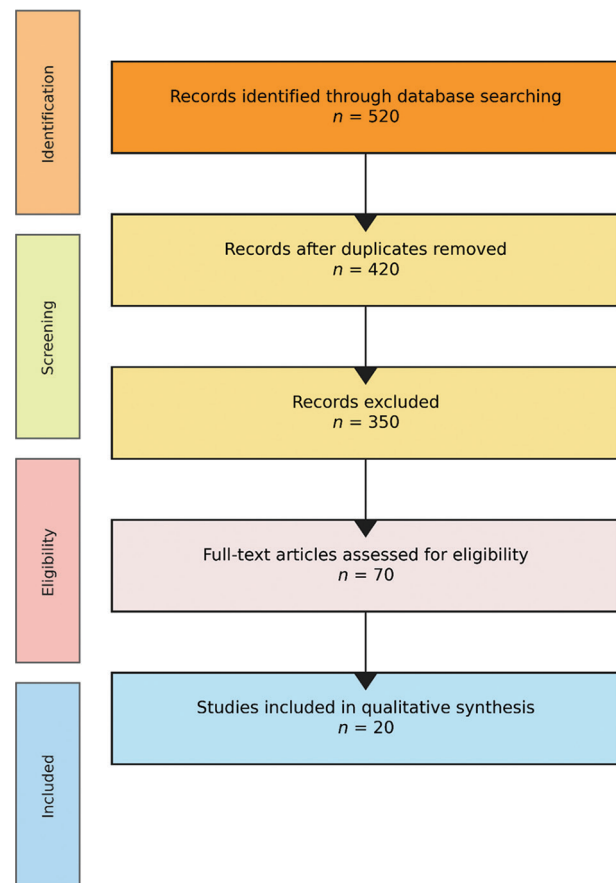


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) 2020 flow diagram
Source: Created by Authors through PRISMA Synthesis.

research gaps, and future research directions. Evidence strength was considered when making recommendations, with the Malaysian tourism context taken into account for applicability.

3. Results and discussion

Data extraction and study details are summarized in Table 2, which presents the 20 reviewed studies by author, year, leading Industry 4.0 innovation, study approach, and principal findings pertinent to sustainable tourism.

3.1. Contextual thematic synthesis of findings

The selected studies demonstrate a global coverage, with studies being undertaken in China, Malaysia, Europe, the Middle East, and multi-country settings. Empirical research and conceptual studies were represented, from small-scale case studies in hotels and heritage areas to large-scale systematic reviews. Although various technologies were represented, such as IoT, blockchain-based technologies, and AR/VR (for VR experiences), AI

Table 1. Systematic literature review method used

Step	Description
Design	Systematic literature review following PRISMA 2020 with predefined protocol
Data sources	Scopus, Web of Science, ScienceDirect, Google Scholar (2015–2023), plus manual search
Search strategy	Search terms: “sustainable tourism” AND (“Industry 4.0,” “AI,” “IoT,” “blockchain,” “big data,” “VR”)
Inclusion criteria	Peer-reviewed articles in English focusing on Industry 4.0 and sustainability in tourism
Exclusion criteria	Excluded: Non-tourism, non-sustainability, non-English, or tech-only without tourism context
Screening process	Title/abstract screening, followed by full-text review; two independent reviewers with consensus

Abbreviations: AI: Artificial intelligence; IoT: Internet of Things; PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-analyses; VR: Virtual reality.

Table 2. Summary of key outcomes for sustainable tourism

Study (author, year)	Tech focus	Type of study	Key outcomes for sustainable tourism
Majid <i>et al.</i> (2023) ¹²	AI (intelligent automation)	Systematic review (213 papers)	Identified five major application themes of AI for sustainability: enhancing tourist experience, preserving heritage, improving quality of life, measuring experiences, and conserving the environment. Found more focus on economic and sociocultural aspects than environmental, indicating a gap in AI addressing environmental sustainability. Proposed an “AI4GoodTourism” framework to guide future AI innovations for sustainability.
Rahmadian <i>et al.</i> (2022) ¹³	Big data analytics	Systematic review (131 papers)	Big data applications in sustainable tourism have emerged since 2016. Big data are used for behavior prediction (e.g., tourist flows) and to support decision-making and policymaking for sustainability. Demonstrated how integrating big data with AI and IoT enables smart tourism services in smart cities. Highlighted challenges: Data quality, privacy, cost, and need for cross-sector data sharing.
Kannan (2024) ¹⁴	AI	Comprehensive review	Reviewed AI integration in tourism operations and customer experience. Concluded that AI-driven personalization and automation improve tourist satisfaction and operational efficiency, while also offering future opportunities for smarter, more sustainable tourism services.
Rane <i>et al.</i> (2023) ¹⁵	AI, blockchain, IoT, AR/VR	Conceptual review (multitech)	Explored all five techs as solutions to tourism’s sustainability challenges (environmental degradation, cultural disruption, and socioeconomic imbalances). Found that: AI enables optimized resource allocation, personalized experiences, and data-driven sustainability strategies; Blockchain creates transparent, traceable supply chains for equitable economic benefits and lower environmental impact; IoT supports real-time environmental monitoring and adaptive conservation measures; AR enriches cultural heritage interpretation, deepening tourist understanding; VR provides virtual experiences that reduce the need for physical travel, cutting carbon footprints. Overall, a technology-driven approach can significantly enhance environmental, social, and economic sustainability in tourism.
Kontogianni <i>et al.</i> (2024) ¹⁶	AI and blockchain	Book chapter (Springer)	Discussed smart tourism through AI and blockchain integration. Emphasized AI’s role in customer-facing smart tourism (chatbots, personalization) and blockchain’s role in secure data management and trust in tourism transactions. Suggested that combining these technologies can improve tourist experience and accountability (e.g., verifying sustainable practices), though empirical validation was noted as a future need.
Treiblmaier (2022) ¹⁷	Blockchain	Handbook chapter (review)	Provided an overview of blockchain applications in tourism (payments, inventory, and loyalty). Highlighted how blockchain can disintermediate travel services and reduce costs and fraud. Emphasized improved transparency and efficiency in tourism operations via smart contracts and decentralized ledgers.
Rashideh (2020) ¹⁸	Blockchain	Conceptual framework	Developed a blockchain framework for tourism. Identified potential benefits: Enhanced security for transactions, reduced operational and commission costs, and greater transparency across stakeholders. Envisioned blockchain for secure identity management (e.g., digital passports, seamless check-ins) and use of cryptocurrency for peer-to-peer payments to build trust in platforms.

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Table 2. (Continued)

Study (author, year)	Tech focus	Type of study	Key outcomes for sustainable tourism
Li and Jiang (2023) ¹⁹	AR	Empirical study (China, survey)	Investigated tourist acceptance of AR for creating memorable experiences. Using the Technology Acceptance Model, found that the perceived usefulness of AR enhancements at attractions leads to higher acceptance. Implies AR can increase tourist engagement and satisfaction, potentially encouraging sustainable behaviors if AR content emphasizes conservation.
Polukhina <i>et al.</i> (2025) ²⁰	VR, digital platforms	Case studies (Russia, transition economy)	Examined digital solutions for sustainable tourism development. Found that VR experiences can substitute physical travel, reducing travel-related emissions and pollution. Also noted that VR and digital platforms raise environmental awareness among tourists by showcasing conservation content. It is concluded that smart tourism tools contribute to sustainability in emerging destinations but require supportive infrastructure.
Zhuang <i>et al.</i> (2022) ²¹	Mobile apps, VR	Quantitative analysis (China, FDI, and tourism)	Analyzed the impact of technology innovation on tourism and the environment. Reported that digital platforms (mobile apps) can foster tourist engagement in sustainable practices (e.g., apps informing tourists about responsible behaviors). In addition, noted that VR can mitigate environmental pressure by offering virtual visits, thereby lowering carbon emissions from tourism.
Farid and Rashid (2024) ²²	IoT	Conceptual paper (smart destinations)	Discussed IoT-enabled “smart destinations.” illustrated how IoT devices in hotels and tourist sites lead to personalized services (smart rooms, automated check-in) and efficient operations. Highlighted IoT-driven energy management and predictive maintenance in hotels (e.g., sensor-based energy savings at Crowne Plaza) to reduce resource waste. It is concluded that IoT improves visitor satisfaction and reduces the environmental footprint of hospitality operations.
Eskerod <i>et al.</i> (2019) ²³	IoT (smart hotels)	Multicase study (five high-end hotels)	Explored drivers for IoT adoption to enhance sustainability in luxury hotels. Found that pressure to reduce hotels’ significant carbon footprint and to cut energy costs were key motivators. IoT-based smart management systems (integrating HVAC, lighting, etc.) enabled guests to control room settings via one interface while optimizing energy use. Identified management support and brand image (green reputation) as additional drivers for implementing IoT innovations.
Yang <i>et al.</i> (2021) ²⁴	Blockchain	Case analysis (heritage tourism)	Demonstrated blockchain’s utility in cultural heritage preservation. By recording and tracking community heritage assets on a tamper-proof ledger, blockchain enhances transparency in managing these resources. This transparency helps ensure that tourism activities around heritage sites remain accountable and sustainable. Authors suggest that such blockchain-based tracking can support community trust and long-term cultural sustainability in tourism.
Rodrigues <i>et al.</i> (2024) ²⁵	Multitech (Industry 4.0)	Systematic review (Heliyon)	Assessed digital transformation in tourism via Industry 4.0. Noted that although many studies examine individual technologies, there is a lack of integrated perspectives on their collective impact on transformative sustainable tourism. This indicates a research gap in understanding synergies among AI, IoT, blockchain, etc.,. Authors call for holistic approaches and more empirical cases of multiple tech adoption.
Capucho <i>et al.</i> (2025) ²⁶	Bibliometrix software for bibliometric mapping	Systematic review and bibliometric analysis of 223 selected papers	It identified three thematic clusters: (i) Sustainable tourism, (ii) tourism, (iii) well-being, and proposed a new taxonomy for sustainable tourism that integrates well-being and sustainable development, enhancing conceptual clarity and supporting balanced tourism planning.
Luu <i>et al.</i> (2025) ²⁷	Digitalization in tourism supply chains under Industry 4.0	Bibliometric review of literature on digitalization in tourism supply chains	Identified research clusters showing a shift from supply chain efficiency to innovation-driven sustainability; highlighted how Industry 4.0 tools can optimize resource use and improve environmental performance in tourism logistics.
Bekele and Raj (2025) ²⁸	Digital transformation in the tourism industry	Bibliometric review and research agenda setting	Mapped four primary research clusters linking digital transformation to tourism growth; stressed the need for sustainable integration of digital tools to enhance resilience and competitiveness of the tourism sector.
Astanakulov <i>et al.</i> (2025) ²⁹	IoT for smart tourism	Thematic analysis of IoT innovations in tourism	Found that IoT can significantly improve tourist experience, resource management, and sustainability monitoring; proposed frameworks for integrating IoT into Tourism 4.0 strategies.

(Cont'd...)

Table 2. (Continued)

Study (author, year)	Tech focus	Type of study	Key outcomes for sustainable tourism
Duarte Alonso <i>et al.</i> (2025) ³⁰	Industry 4.0 adoption in hospitality	Case study of Vietnamese hospitality organizations	It identified 11 dimensions of Industry 4.0 application in hospitality, with benefits including improved energy efficiency, reduced waste, and enhanced service customization to support sustainable tourism models.
Sjukriana <i>et al.</i> (2025) ³¹	Event technology in hospitality and tourism	Systematic review	Found that technology adoption in events is driven by perceived ease of use and usefulness; emphasized the potential to reduce environmental impact through virtual and hybrid event formats, contributing to sustainability goals.

Abbreviations: AI: Artificial intelligence; AR: Augmented reality; HVAC: Heating, ventilation, and air conditioning; IoT: Internet of Things; VR: Virtual reality.

and data analytics were the most frequently highlighted tools.³²

Scientific interest in this area has increased significantly over the past 5–6 years due to the intersection between digitalization and sustainability agendas. In a qualitative review, several recurring themes emerged regarding how Industry 4.0 technologies facilitate sustainable tourism. These are shown in Table 3 with representative examples from the literature.

3.1.1. Thematic insights

Industry 4.0 technologies are contributing to the three pillars of sustainable tourism. Environmentally, AI, IoT, and VR technologies reduce energy and resource consumption, lower emissions, and facilitate the preservation of natural and cultural heritage sites. AI-based energy management platforms minimize hotel electricity usage, IoT products offer real-time environmental monitoring, and VR enables low-impact exploration of sensitive locations, thereby reducing ecological pressure.³³

In sociocultural terms, AR/VR has been effective in tourism education and awareness, facilitating deeper cultural appreciation and learning for sustainability. Blockchain-based transparency systems help empower stakeholders by revealing how tourism benefits are distributed, thereby enhancing perceptions of fairness.

Economically, AI and automation increase efficiency and reduce costs, presenting a sound business case for investment. Technologies, such as VR-based tourist products and intelligent tourism apps, create new sources of revenue and attract niche markets. Blockchain removes intermediaries, raising returns for suppliers and reducing costs for consumers. As reported in Malaysia, AR/VR tourism pilots demonstrate how new products can simultaneously increase competitiveness and instill sustainability, as shown in Figure 2.

Synthesizing these findings indicates that Industry 4.0 technologies are not an end in themselves; rather, they serve as facilitators of sustainable tourism outcomes. AI

and big data enable predictive outcomes to maximize resources and minimize risks of overcrowding. IoT enables intelligent destinations for achieving energy and water efficiency. Blockchain enables accountability and eco-certification. AR/VR optimizes experience while providing alternatives to physical travel.³³ All these technologies, together, balance economic recovery with sustainability in post-pandemic tourism environments.

3.2. Environmental impacts of AI in tourism 4.0

Environmental consequences are the most well-documented in the literature examined. AI-powered hotel energy systems are said to minimize electricity usage by up to 20%, whereas IoT-powered conservation initiatives enable real-time monitoring of ecosystems. Digital tourism and virtual tours reduce travel intensity, resulting in quantifiable carbon savings.

However, the evidence is not entirely positive. Several studies^{32,33} reported that small- and medium-sized enterprises (SMEs) incurred significant upfront costs that limited adoption. Others were alert to rebound effects, whereby efficiency savings lead to greater demand, thereby counteracting environmental gains. Rodrigues *et al.*²⁵ provided a comprehensive review of Industry 4.0 implications for tourism, noting that while technological adoption is widespread, integrated frameworks linking multiple technologies to sustainability outcomes remain underdeveloped.³⁴

In addition, most evaluations rely on short-term pilot studies; there is insufficient longitudinal data to determine if environmental gains are sustained at scale. This implies that AI is an enabler of environmental sustainability but is contingent upon governance structures, affordability, and regular monitoring.

3.3. Governance impacts of AI in Tourism 4.0

AI also assists in enhancing tourism governance. Research indicates that AI-based dashboards and data platforms increase transparency through real-time monitoring of visitor movement, energy consumption, and emissions.

Table 3. Thematic synthesis of findings

Thematic category	Role of Industry 4.0 tech in sustainable tourism	Illustrative evidence
1. Resource efficiency and environmental conservation	Technologies drive more efficient use of resources and the reduction of tourism’s environmental footprint. AI and big data enable data-driven resource management (e.g., optimizing energy and water use in hotels, predicting tourist flows to prevent overcrowding). IoT sensors monitor environmental conditions in real time, enabling adaptive conservation measures (e.g., adjusting facilities usage based on wildlife activity). AR and VR can substitute or complement physical travel, helping lower carbon emissions by offering virtual experiences. Overall, Industry 4.0 innovations support greener operations and informed environmental stewardship in tourism.	AI-driven smart systems in destinations reduce energy waste (smart grids, HVAC). Big data analysis helps managers plan visitor distribution to avoid overuse of natural sites. IoT deployments in parks track soil, air, and wildlife data to inform carrying capacity decisions. VR “virtual tourism” experiences have demonstrably cut down actual visits in some cases, curbing emissions and pollution.
2. Enhanced tourist experience and education	Industry 4.0 tech enables more immersive, personalized, and educational tourism experiences that align with sustainability. AI-powered personalization (recommendation engines, chatbots) helps tourists with eco-friendly options and tailors experiences without extra resource strain. IoT creates “smart” service environments (e.g., smart hotels, attractions) that improve convenience (e.g., keyless entry, automated transit info) and encourage responsible behavior (e.g., apps that nudge energy-saving). AR enriches on-site experiences by overlaying interpretive content about heritage or ecology, educating tourists on sustainability and cultural significance. VR provides enjoyment and pre-trip learning about destinations, raising awareness, and reducing impulsive travel. By making sustainable choices attractive through a tech-enhanced experience, tourists’ satisfaction and willingness to support conservation increase.	Airbnb’s AI algorithms personalize travel plans, including suggesting less crowded, eco-friendly attractions, enhancing the experience while avoiding overtourism. Smart destination apps (mobile platforms) engage tourists with real-time guidance and sustainability tips (e.g., water-saving reminders). An AR application in a Malaysian heritage site guides tourists with cultural stories, making the visit more engaging and meaningful (local example). Studies show AR can significantly improve the “memorable tourism experience” for visitors, which destinations leverage to promote environmental education.
3. Transparency, trust, and governance	Blockchain and data analytics improve transparency in tourism supply chains and governance, leading to more sustainable practices. Blockchain’s immutable ledgers enable tracing of tourism products and services—for instance, tracking if a hotel’s operations meet sustainability certifications or if community tourism funds are distributed. This builds trust among consumers and stakeholders that sustainability claims are genuine (preventing “greenwashing”). Smart contracts can ensure fair payments (e.g., automatic carbon offset contributions). Open data platforms and big data dashboards (often government-led) enable monitoring of tourism impacts and evidence-based policy interventions. Collectively, these technologies encourage accountability: tourism businesses are incentivized to adopt sustainable operations, knowing that data are transparent. Governments and communities gain tools to enforce regulations and share benefits equitably.	Blockchain pilots in tourism (e.g., in Hungary) have improved transaction security and transparency between tourists and service providers. Tourism authorities using big data dashboards can publicly share indicators, such as footfall in protected areas or waste generated, pressuring operators to reduce impacts. Studies reported that blockchain could verify the authenticity of heritage crafts and ensure revenue goes to local artisans. Such transparency mechanisms help tourists make informed choices and foster trust in sustainability certifications (e.g., a blockchain-based ecolabel for hotels that travelers can verify).
4. Cultural heritage preservation and social inclusiveness	Several technologies help protect cultural and natural heritage and promote inclusive community development. AR and VR offer new ways to experience cultural heritage sites without causing wear and tear on artifacts or disturbance to communities. Virtual tours can reduce the need for large numbers of tourists at fragile sites while still generating interest and educational value. AI and big data tools aid in managing visitor impact on heritage (e.g., predictive models for site erosion based on visitor numbers). Blockchain can empower local communities by recording their cultural assets and ensuring benefits from tourism are returned to them transparently. IoT can be used in heritage sites for surveillance to prevent vandalism or to control microclimates in sensitive museums. Overall, Industry 4.0 can mitigate the negative impacts of tourism on heritage and ensure communities remain central beneficiaries.	Augmented reality apps allow tourists to visualize historical scenes or artifacts in situ, enriching appreciation without physical touching or damaging them. VR heritage tours (e.g., virtual walk-throughs of UNESCO sites) gained popularity during COVID-19, showing they can provide access while reducing congestion at sites. Community-based tourism projects are testing blockchain for the transparent sharing of profits and funding of local conservation, addressing trust issues with external tour operators. In addition, AI translation and digital platforms provide residents with a greater voice and involvement in tourism experiences than the traditional approach, supporting sociocultural sustainability.
5. Data-driven planning and policy	Widespread adoption of analytics (big data, AI) and IoT feeds is enabling smarter tourism planning and policy geared toward sustainability. Destination managers and policymakers use predictive models to anticipate	Big data analyses have shown their usefulness in tourism strategy—for instance, analyzing geotagged social media to identify overvisited hotspots and then implementing

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Table 3. (Continued)

Thematic category	Role of Industry 4.0 tech in sustainable tourism	Illustrative evidence
	anticipate tourism demand and environmental impacts, allowing proactive measures such as visitor caps or dynamic pricing to prevent overtourism. Scenario simulations (e.g., using AI or digital twins) help evaluate sustainability strategies (like the impact of diverting tourists to alternative sites). Real-time data from sensors and social media provide early warnings of issues (wildfires, coral reef stress, crowding) such that authorities can respond quickly. These approaches support evidence-based decision-making and align tourism development with sustainability targets (e.g., SDGs). Importantly, data-driven insights help balance economic benefits with ecological limits and community well-being, guiding policies on destination growth, transportation, and resource management.	measures to redistribute visitor flows. Several cities (such as Amsterdam and Barcelona) employ AI to predict peak tourist congestion and adjust city services or issue travel advisories, thereby reducing strain on infrastructure. In national parks, IoT-based visitor counting and environmental monitoring inform adaptive management plans each season. Such data-driven initiatives result in more adaptive, resilient tourism systems that can maintain sustainability even as tourism volumes change.

Abbreviations: AI: Artificial intelligence; AR: Augmented reality; HVAC: Heating, ventilation, and air conditioning; IoT: Internet of Things; SDGs: Sustainable Development Goals; UNESCO: United Nations Educational, Scientific, and Cultural Organization; VR: Virtual reality.

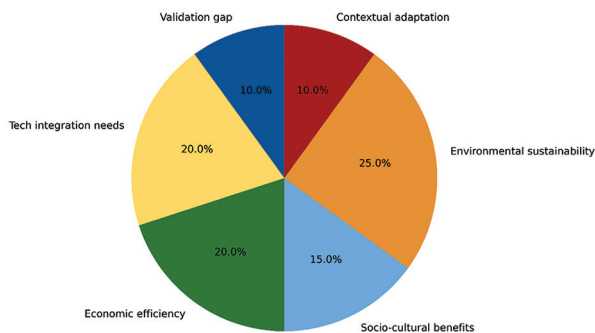


Figure 2. Distribution of research emphasis in Industry 4.0 and sustainable tourism. Environmental sustainability represents the largest share of research focus, followed by economic efficiency and technology integration needs.

Source: Created by the authors based on synthesized review data.

Blockchain technologies, though less studied, hold potential for transparent eco-certification and reducing fraud in tourism supply chains. They can enhance regulatory control and accountability among stakeholders.³⁴ As emphasized by recent reviews, integrating Industry 4.0 into sustainability agendas requires not only technological innovation but also supportive governance, cross-sectoral alignment, and inclusive stakeholder engagement.

However, governance-based constraints are evident. Ethical issues regarding data privacy are rarely addressed, although travelers are likely to oppose surveillance-based monitoring.³⁵ Smaller companies and rural operators are likely to be left out of digital governance structures, resulting in disparities. Furthermore, policymaking mechanisms to help control responsible AI use in tourism are also lacking. Consequently, governance impacts become conditional and vulnerable: AI can enhance transparency only if it is embedded within broader institutional support frameworks that ensure fairness and inclusion.

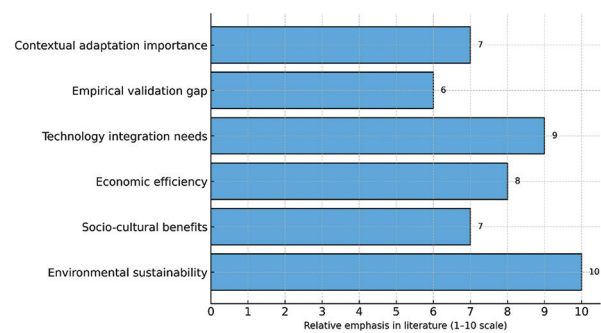


Figure 3. Relative emphasis of key research themes in Industry 4.0 and sustainable tourism (1–10 scale). Environmental sustainability shows the highest emphasis (score = 10), followed by technology integration (score = 9) and economic efficiency (score = 8).

Source: Created by the authors based on synthesized review data.

3.4. Critical problems and paradoxes

While most of the literature is positive, a critical synthesis shows contradictions. AI forecasting models are praised for helping predict and manage overtourism, but few studies show that these forecasts have led to long-term policy change or quantifiable visitor redistribution. Blockchain is commonly referred to as a transparency tool, but in practice, its implementation is rare due to its technical sophistication and the uncertainty in returns on investment.³⁴ AI-based personalization is cherished to enhance tourist experiences, but also denounced for violating privacy and eroding confidence. Figure 3 depicts how the reviewed literature reconciles beneficial consequences with critical issues.

Most benefits reported are from pilot studies or conceptual models, often across limited time perspectives. There is a lack of longitudinal studies examining sustained influences on emissions, conservation, or reforms of governance. These inconsistencies highlight that AI and

Tourism 4.0 must be treated as possible facilitators, rather than certainties.

3.5. Research gaps identified

The review also exposes important research gaps, shown in Figure 4. There are limited studies that combine multiple technologies into integrated frameworks; most compartmentalize AI, IoT, or blockchain separately. Strong empirical case studies remain rare, especially in the developing world, and longitudinal data are sparse. Measurement issues continue, although promises of carbon savings or transparency gains are routine; there are few studies with hard, measurable numbers. Ethical and privacy aspects are not yet well explored, as are the threats of digital exclusion. Geographically, the research is skewed toward Europe and China, whereas Southeast Asia, Africa, and Latin America remain somewhat underrepresented.

The small dataset of 20 included studies further limits generalizability. Although the studies provide valuable information, conclusions must be viewed as indicative, rather than definitive. More comprehensive studies are needed to synthesize evidence across contexts and technologies. This aligns with recent evidence that highlights the need for longitudinal, integrated approaches to Industry 4.0 and sustainability.³⁶

3.6. Synthesis and implications

In general, AI in Tourism 4.0 shows great potential to drive sustainability. Environmentally, AI and linked technologies support efficiency gains, resource savings, and emissions reductions. At the governance level, AI and blockchain help support transparency and accountability. Contradictions exist, though: adoption is expensive, benefits are unequal, privacy issues are unresolved, and evidence over the long term is lacking.

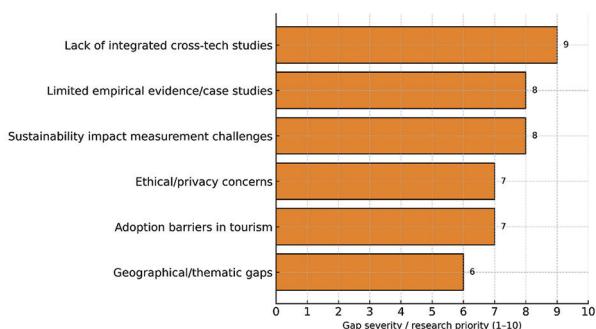


Figure 4. Identified gaps in Industry 4.0 and sustainable tourism. The figure highlights limited longitudinal evidence, fragmented multi-technology integration, under-representation of developing regions, and insufficient attention to ethics, privacy, and inclusiveness.

Source: Created by the authors based on synthesized review data.

For Malaysia, these results indicate that while there are early pilots and policies, system integration has yet to be achieved. The nation is at a mid-evolutionary point: beyond disconnected projects but not yet a fully entrenched Tourism 4.0 system. Scaling AI-enabled solutions, therefore, needs to be supported not just by technical infrastructure but also by inclusive governance frameworks, ethical safeguards, and longitudinal monitoring systems. The following section presents in-depth recommendations for Malaysia directly linked to the environmental and governance findings of the review.

While the literature generally highlights positive contributions of Industry 4.0 technologies to sustainable tourism, it also reveals critical tensions. Adoption remains uneven, especially for SMEs with limited resources, and sustainability claims are often based on short-term pilot projects rather than longitudinal evidence. Moreover, the risks of privacy intrusion, digital exclusion, and cost inefficiencies are underexplored in numerous studies. This limits the ability to fully understand both the theoretical implications of digital transformation for sustainable development and the practical challenges faced by tourism enterprises. A deeper critical reflection indicates that Industry 4.0 cannot be assumed to guarantee sustainability; rather, its benefits depend on careful design, supportive governance, and alignment with local contexts.

4. Future research directions

Based on the identified gaps, the review proposes several future research directions (Figure 5):

- (i) Longitudinal case studies and experiments: Destinations must work with researchers to deploy technologies and monitor outcomes. For example, a city or resort may be a “living lab” where IoT, AI, and AR projects are implemented to increase sustainability,

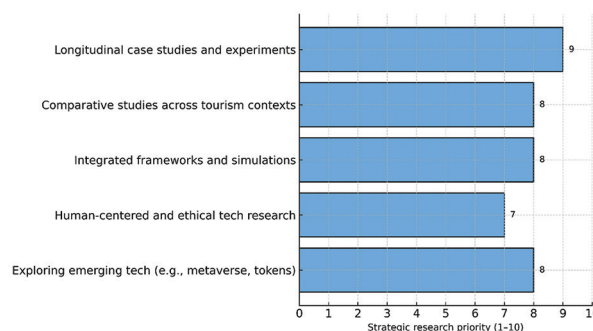


Figure 5. Strategic future research agendas for sustainable Tourism 4.0. This framework outlines key directions, including longitudinal case studies, cross-context comparative analyses, integrated multitechnology simulations, participatory human-centered design, and ethical artificial intelligence adoption.

Source: Created by the authors based on synthesized review data.

and researchers monitor the effect pre- and post-deployment on energy usage, tourist satisfaction, community livelihoods, etc. Long-term monitoring will determine the efficacy of tech solutions and whether rebound effects occur (e.g., does refining something make it more efficient or lead to increased demand?).

- (ii) Cross-context comparative analysis: Future studies can compare how Industry 4.0 affects sustainable tourism across different contexts, for example, a tech-savvy city vs. a remote ecotourism community. This can determine contextual factors and best practices. Malaysia, with its mix of urban (Kuala Lumpur) and natural (Borneo, islands) destinations, is an excellent country for cross-context comparative analyses on how technology adoption strategies would differ.
- (iii) Integrated frameworks and simulations: Research must strive to design integrated frameworks that combine multiple technologies to achieve maximum gains in sustainability. Simulation packages, such as system dynamics or agent-based models, can be employed to simulate a destination with various tech interventions (like simulating a 10% reduction in tourists through the adoption of VR or a 20% increase in IoT efficiency and examining how the system responds).³⁵ This would be useful in forecasting the impacts of collaborative interventions and guiding real-life trials.
- (iv) Human science and ethical research: Since this topic is sociotechnical, human science research is also required. These are research on the acceptance of tech-mediated tourism experiences (will tourists accept virtual experiences as alternatives or just complements?), employee adaptation to the automation of tourism services, and regulatory research on data privacy and ethics. For example, exploring tourist satisfaction and learning gains from AR/VR experiences specifically designed with sustainability can help create improved content. In addition, co-designing technology solutions for tourism with local communities may be a research area (participatory design approach) in which solutions are well accepted and culturally appropriate.
- (v) Technological innovations and new opportunities: The pace of technology is rapid. Further studies should monitor emerging technological trends, such as AI-powered predictive analytics (even more sophisticated), blockchain tokens or rewards for green behavior (e.g., earn tokens for being off-beat sites), IoT convergence with renewable energy (hotels leveraging IoT to use solar/wind maximally), and the Metaverse or enhanced VR for travel. Evaluating the potential benefits and drawbacks of such revolutionary trends

prior to their full adoption within the mainstream tourism market can position the industry to leverage them ethically.³⁷

In essence, an interdisciplinary approach will be crucial—involving tourism scholars, data scientists, engineers, and social scientists to collaboratively address these research agendas. This will ensure that the next wave of tourism technology research is holistic, impact-oriented, and in alignment with sustainability imperatives.

The findings verify the initial research propositions that Industry 4.0 technologies, especially AI, have significant but uneven impacts on sustainability outcomes. Evidence confirms their contribution to environmental efficiency and governance transparency, but also reveals challenges, such as costs, privacy, and limited scalability. Based on these insights, further studies should expand longitudinal evaluations, explore cross-technology integration, and examine adoption in developing-country contexts, including Malaysia.

5. Recommendations for Malaysia's tourism industry

Although this review synthesizes global literature, Malaysia is chosen for contextual recommendations because it represents a developing economy at a transitional stage of Tourism 4.0 adoption. The country has launched initiatives, such as MyDIGITAL and Smart Tourism 4.0, yet integration of AI into governance and sustainability remains fragmented. This makes Malaysia an appropriate case for illustrating how global lessons can be localized to strengthen both environmental outcomes and institutional governance in tourism.

Worldwide, discussions on Tourism 4.0 highlight that AI, IoT, blockchain, big data, and AR/VR can bring sustainability benefits, but are implemented piecemeal and without integration. Malaysia is not beginning from zero. There are national policies, including MyDIGITAL, the National Tourism Policy 2020–2030,³⁷ and the Malaysia Smart Tourism 4.0, that have already introduced the significance of tourism digitalization. Pilot AR/VR heritage experiences, fintech sandboxes for regulation, and IoT-enabled monitoring initiatives in ecotourism destinations are also early indicators. Most initiatives, however, are still fragmented or small in scale. The following recommendations are thus adjusted for mid-evolution: Malaysia has progressed beyond standalone pilots but is not yet at a fully institutionalized, interconnected smart tourism ecosystem.

5.1. Invest in smart tourism infrastructure

Malaysia's digital economy agenda already encompasses infrastructure expansion, but has uneven tourism-specific

deployment.³⁸ As a next step for MyDIGITAL and Smart Tourism 4.0, investment needs to focus on broadband availability, 5G deployment, and IoT-sensor networks in key destinations. For instance, IoT monitoring in Taman Negara or Sabah's marine parks would facilitate data-driven visitor management, while growing "smart city" infrastructure in Kuala Lumpur or Penang would streamline transport flows and ease congestion. These infrastructures are the bedrock for AI-powered analytics, driving both environmental protection and enhanced tourist experiences. In contrast to previous disjointed pilots, this proposition locates infrastructure as an integrated national priority for tourism sustainability.

5.2. Facilitate tech-enabled sustainable experiences

Malaysia has experimented with AR heritage trails and isolated VR ecotourism activities, yet these continue as standalone initiatives. A synergistic program, such as national AR trails in George Town and Malacca, or VR tourism packages highlighting marine biodiversity in Sabah, would turn these small-scale experiments into mass market tourism products. These programs not only appeal to digitally connected tourists but also mitigate pressure on vulnerable ecosystems by providing immersive, low-impact options. Public-private partnerships, digital hackathons, and seed-funding programs might be used to produce locally centered content that fosters both heritage appreciation and conservation awareness. This extends existing pilots but converges them into a more cohesive national digital tourism system.³⁹

5.3. Use blockchain to ensure transparency and certification

Malaysia has already run sustainability certification programs, yet transparency and verification remain issues. By utilizing its fintech regulatory sandbox, Malaysia can test blockchain-based platforms in holding and authenticating eco-certifications, carbon accounting, and community benefit-sharing schemes. A national "Green Tourism Blockchain" would allow tourists to immediately check green claims while encouraging companies to take sustainable actions. Token-based systems could further incentivize environmentally friendly behavior (e.g., booking low-carbon tours) through redeemable rewards. This suggestion thus capitalizes on Malaysia's fintech preparedness to put the nation at the vanguard of open and accountable sustainable tourism management.³⁹

5.4. Inclusive innovation and capacity building

Previous initiatives, such as the Malaysia Tourism Transformation Plan, focused on training, but SMEs and rural operators do not always have the resources to adopt

digital tools. To bridge this gap, Malaysia needs to create targeted accelerators and incubators that integrate digital capabilities to SMEs and community-based businesses, ranging from IoT system maintenance to AR/VR content development. Inclusive innovation ensures that rural guides, indigenous entrepreneurs, and small operators are not left behind in the digital economy. For example, upskilling locals to operate drone-based monitoring or to co-create AR heritage stories would create employment while retaining cultural authenticity. By integrating inclusivity, Malaysia reduces excessive reliance on external providers and promotes culturally appropriate solutions.⁴⁰

5.5. Policy integration and multistakeholder collaboration

Malaysia's tourism administration now mentions digitalization within strategic papers, but it remains fragmented across ministries. In line with the National Tourism Policy 2020–2030,⁴¹ there needs to be a multistakeholder platform comprising the Ministries of Tourism, Environment, and Communications, as well as academia, SMEs, and tech companies to harmonize standards, ensure the ethical use of data, and establish measurable sustainability parameters. Pilot work with universities, for example, testing AI-controlled tourist dispersion systems in Langkawi or Penang, can provide evidence-based benefits, informing policy formulation. A larger co-creation platform, in support of the Malaysia Tourism Transformation program, would guarantee solutions are not only technologically innovative but also ethically founded, socially inclusive, and environmentally sustainable.⁴²

Malaysia stands at a crossroads: It has set the stage for Tourism 4.0 with strategic policies and pilot projects, yet systematic integration remains unfinished.^{35,37} By advancing infrastructure, expanding sustainable digital experiences, embracing blockchain transparency, developing inclusive capacity, and harmonizing multistakeholder policies, Malaysia can turn its disjointed efforts into a streamlined, sustainable tourism system. These recommendations thus sit at the midpoint of system development, building on what is there while laying the foundation for an entirely institutionalized, people-first, and sustainable smart tourism future.^{25,43,44}

This review is based on a relatively small but highly targeted set of 20 studies. While sufficient for capturing key themes, the limited studies require cautious interpretation, particularly regarding emerging technologies, such as blockchain. Future reviews with expanded datasets and longitudinal evidence will further consolidate these findings.

6. Conclusion

This review demonstrates that Industry 4.0 technologies, particularly AI within the Tourism 4.0 framework, contribute to sustainable development by promoting environmental efficiency, transparent governance, and resilience in the tourism sector. Environmentally, AI and IoT enable measurable reductions in energy and resource consumption, while VR and AR lower ecological pressure by providing low-impact visitor experiences. From a governance perspective, blockchain and AI-based monitoring systems enhance accountability, certification, and decision-making. Together, these technologies help tourism enterprises integrate sustainability into their operations, balancing growth with conservation.

The findings suggest that smart tourism infrastructure, interactive and educational digital experiences, blockchain-enabled transparency, inclusive capacity-building programs, and multistakeholder policy integration are key enablers of sustainable tourism. Effective adoption, however, requires a balanced approach that combines technological innovation with community engagement, environmental sustainability, and cultural authenticity.

The review's main achievement lies in synthesizing how AI-centered Industry 4.0 innovations interact with environmental and governance dimensions of sustainability. However, the study has limitations: the dataset comprises 20 studies, and the evidence is heavily skewed toward short-term pilots and emerging technologies, such as blockchain, which remain under-researched. These limitations imply that conclusions must be treated as indicative rather than definitive, and further longitudinal and context-specific studies are required.

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References

1. Rane N, Choudhary S, Rane J. Sustainable tourism development using leading-edge artificial intelligence (AI), blockchain, Internet of Things (IoT), augmented reality (AR), and virtual reality (VR) technologies. *SSRN Electron J.* 2023;1:22.
doi: 10.2139/ssrn.4642605
2. Gomes S, Lopes JM, Ferreira L. Looking at the tourism industry through the lenses of Industry 4.0: A bibliometric review of concerns and challenges. *J Hosp Tour Insights.* 2024;7(1):436-457.
doi: 10.1108/JHTI-01-2023-0028
3. Stankov U, Gretzel U. Tourism 4.0 technologies and tourist experiences: A human-centered design perspective. *Inf Technol Tour.* 2020;22(3):477-488.
doi:10.1007/s40558-020-00172-y
4. Buhalis D, Efthymiou L, Uzunboylu N, Thrassou A. Charting the progress of technology adoption in tourism and hospitality in the era of Industry 4.0. *Eur Med J Bus.* 2024;19(1):1-20.
doi: 10.1108/EMJB-01-2023-0025
5. Boluk KA, Cavaliere CT, Higgins-Desbiolles F. A critical framework for interrogating the United Nations Sustainable Development Goals 2030 Agenda in tourism. *J Sustain Tour.* 2019;27(7):865-880.
doi: 10.1080/09669582.2018.1479037
6. Dixit P. *Tourism and Technology: The Future.* New Delhi, India: Educohack Press; 2025.
7. Basu M, editor. Tech-driven horizons: Pioneering sustainable tourism for environmental resilience and SDGs triumph. In: *The Need for Sustainable Tourism in an Era of Global Climate Change: Pathway to a Greener Future.* Bingley, UK: Emerald Publishing; 2024. p. 215-247.
doi: 10.1108/978-1-80455-178-020241011
8. Topsakal Y. Artificial intelligence-based sustainable tourism planning: a conceptual model proposal. In: Çetinkaya MY, Özdemir M, editors. *Advancing Smart Tourism Through Analytics.* Hershey, PA: IGI Global; 2025. p. 65-94.
doi: 10.4018/978-1-6684-9452-8.ch004

9. Pencarelli T. The digital revolution in the travel and tourism industry. *Inf Technol Tour*. 2020;22(3):455-476.
doi: 10.1007/s40558-019-00160-3
10. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*. 2021;372:n71.
doi: 10.1136/bmj.n71
11. Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Med*. 2009;6(7):e1000097.
doi: 10.1371/journal.pmed.1000097
12. Majid GM, Tussyadiah I, Kim YR, Pal A. Intelligent automation for sustainable tourism: A systematic review. *J Sustain Tour*. 2023;31(11):2421-2440.
doi: 10.1080/09669582.2022.2155904
13. Rahmadian E, Feitosa D, Zwitter A. A systematic literature review on the use of big data for sustainable tourism. *Curr Issues Tour*. 2022;25(11):1711-1730.
doi: 10.1080/13683500.2021.1910217
14. Kannan V, Zhang T, Li H. A review of the intelligent condition monitoring of rolling element bearings. *Machines*. 2024;12(7):484.
doi: 10.3390/machines12070484
15. Rane N, Choudhary S, Rane J. Enhanced product design and development using artificial intelligence (AI), virtual reality (VR), augmented reality (AR), 4D/5D/6D printing, Internet of Things (IoT), and blockchain: Review. *Virtual Real Augment Real Digit Des*. 2023;4:1-12.
doi: 10.2139/ssrn.4680072
16. Kontogianni A, Alepis E, Virvou M, Patsakis C. *Smart Tourism-the Impact of Artificial Intelligence and Blockchain*. Berlin/Heidelberg, Germany: Springer; 2024.
doi: 10.1007/978-3-031-42076-2
17. Treiblmaier H. Blockchain and tourism: Paradoxes, misconceptions, and a research roadmap. *Tour Econ*. 2022;28(7):1956-1960.
doi: 10.1177/1354816620957621
18. Rashideh W. Blockchain technology framework: Current and future perspectives for the tourism industry. *Tour Manag*. 2020;80:104125.
doi: 10.1016/j.tourman.2020.104125
19. Li S, Jiang S. The technology acceptance on AR memorable tourism experience-The empirical evidence from China. *Sustainability*. 2023;15(18):13349.
doi: 10.3390/su151813349
20. Polukhina A, Sheresheva M, Napolskikh D, Lezhnin V. Digital solutions in tourism as a way to boost sustainable development: Evidence from a transition economy. *Sustainability*. 2025;17(3):877.
doi: 10.3390/su17030877
21. Zhuang Y, Yang S, Razzaq A, Khan Z. Environmental impact of infrastructure-led Chinese outward FDI, tourism development and technology innovation: A regional country analysis. *J Environ Plann Manag*. 2023;66(2):367-399.
doi: 10.1080/09640568.2022.2048502
22. Farid MT, Rashid M. Unleashing the potential of Industry 4.0: Analyzing Pakistan's tourism in the global arena. *J Excellence Soc Sci*. 2024;3(2):157-187.
23. Eskerod P, Hollensen S, Morales-Contreras MF, Arteaga-Ortiz J. Drivers for pursuing sustainability through IoT technology within high-end hotels-an exploratory study. *Sustainability*. 2019;11(19):5372.
doi: 10.3390/su11195372
24. Yang Y, Zhang CX, Rickly JM. A review of early COVID-19 research in tourism: Launching the Annals of Tourism Research's curated collection on coronavirus and tourism. *Ann Tour Res*. 2021;91:103313.
doi: 10.1016/j.annals.2021.103313
25. Rodrigues V, Breda Z, Rodrigues C. The implications of Industry 4.0 for the tourism sector: A systematic literature review. *Heliyon*. 2024;10(11):e27621.
doi: 10.1016/j.heliyon.2024.e27621
26. Capucho J, Leitão J, Alves H. Mapping and linking well-being, tourism economics, sustainable tourism and sustainable development: An integrative systematisation of the literature and bibliometric analysis. *Discov Sustain*. 2025;6(1):291.
doi: 10.1007/s43621-025-00367-5
27. Astanakulov O, Balba ME, Khushvakt K. IoT innovations for transforming the future of the tourism industry: Towards smart tourism systems. *J Intell Syst*. 2025;34(2):145-162.
doi: 10.1515/jisys-2024-0019
28. Bekele H, Raj S. Digitalization and digital transformation in the tourism industry: A bibliometric review and research agenda. *Tour Rev*. 2025;80(4):894-913.
doi: 10.1108/TR-07-2023-0509
29. Duarte Alonso A, Kim OVT, Tran TD. Exploring the relationships between Industry 4.0 adoption and business model: The case of Vietnamese hospitality organisations. *Int J Hosp Tour Manag*. 2025;15(1):50-68.
30. Luu NTM, Pham TH, Siriwardana A. Bibliometric review of digitalization in tourism supply chains in the context of Industry 4.0. *Strateg Change*. 2025;34(2):123-140.
doi: 10.1002/jsc.2807

31. Sjukriana J, Hanafiah MH, Asyraff MA, Kusumah G. Unveiling the landscape of event technology adoption in the hospitality and tourism industry: Insights from a systematic literature review. *Int J Event Fest Manag.* 2025;16(2):207-228. doi: 10.1108/IJEFM-06-2024-0077
32. Gonzaga S. The role of prototyping in participatory design projects. In: Dias P, Santos R, editors. *International Conference on Design and Digital Communication.* Cham, Switzerland: Springer Nature; 2024. p. 687-700. doi: 10.1007/978-3-031-68017-3_52
33. Au Yong HN, Kalhor M, Morrison C, Hanna D, Rehman HM. Community-driven sustainability practices in cultural heritage tourism: A qualitative study. *Qual Quant.* 2025;59:1-21. doi: 10.1007/s11135-025-02444-9
34. MyDIGITAL. *Malaysia Digital Economy Blueprint.* Putrajaya, Malaysia: Government of Malaysia, Ministry of Economy; 2021.
35. AlAfnan MA, Mohdzuki SF. Malaysia's National Blockchain Roadmap 2021-2025: A critical discourse analysis of focus, goals, and challenges. *World J Engl Lang.* 2024;14(5):482-492. doi: 10.5430/wjel.v14n5p482
36. MyDIGITAL. *Support Pours In for the MyDIGITAL Initiative and National 4IR Policy.* Putrajaya, Malaysia: Government of Malaysia, MyDIGITAL; 2022.
37. AlAfnan MA, Mohdzuki SF. Malaysia's National Blockchain Roadmap 2021-2025: A critical discourse analysis of focus, goals, and challenges. *World J Engl Lang.* 2024;14(5):482-492. doi: 10.5430/wjel.v14n5p482
38. Government of Malaysia. *National 4IR Policy.* Putrajaya, Malaysia: MyDIGITAL, Ministry of Science, Technology and Innovation; 2023.
39. Tourism Malaysia, Ministry of Tourism, Arts and Culture. *National Tourism Policy 2020-2030-Executive Summary.* Putrajaya, Malaysia: Tourism Malaysia; 2020.
40. Malaysian Investment Development Authority (MIDA). *Smart Tourism: Future of Tourism in Malaysia.* Kuala Lumpur, Malaysia: MIDA; 2021.
41. Tourism Malaysia. *Smart Tourism 4.0 to be Tourism Game-Changer for Malaysia.* Kuala Lumpur, Malaysia: Tourism Malaysia; 2018.
42. Amir S, Nur'Hidayah Dura N, Yusof,MA, Nakamura H, Nong RA. Challenges of smart tourism in Malaysia eco-tourism destinations. Planning Malaysia. *J Malaysian Inst Plan* 2020;18(4):442-451. doi: 10.21837/pm.v18i14.844
43. Al-Qudah AA, Alzoubi HM, Al-Debei MM, Al-Dmour AM, Masadeh R, Abualoush SH. The convergence of artificial intelligence and sustainability reporting: A systematic review of applications, challenges and future directions. *Bus Strateg Environ.* 2024;33(1):70090. doi: 10.1002/bse.70090
44. Kumar RR, Sharma GD, Singh SK. Integrating Industry 4.0 for enhanced sustainability: Pathways and prospects. *J Clean Prod.* 2024;437:140355. doi: 10.1016/j.jclepro.2024.140355