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Review Article

Leveraging digitalization in geoheritage and geoparks: Analysis of advancements and trends through bibliometric analysis and the antecedents, decisions, outcomes-theories, contexts, methods (ADO-TCM) framework

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ABSTRACT

This study aims to systematically analyze the role and trends of digitalization in geoheritage and geopark management, identifying research gaps and future opportunities to support sustainable development and policy-making. It examines the growing trend of leveraging digitalization in geoheritage and geopark management to drive economic growth, cultural education, and sustainability, aligning with the Sustainable Development Goals (SDGs). Utilizing a systematic literature review (SLR) guided by PRISMA 2020 and bibliometric analysis with VOS viewer, it identifies key research trends and gaps. A major novelty of this study lies in the first-time application of the antecedents, decisions, outcomes-theories, contexts, methods (ADO-TCM) framework to analyze digitalization in geoheritage and geoparks. The findings, derived from 138 scholarly articles, reveal that while digital tools are increasingly explored in tourism and heritage management, their specific role in geoheritage and geopark settings remains underexamined. The study highlights digitalization's potential to promote sustainability, enhance economic development, and improve educational outcomes. It offers actionable insights for various stakeholders. Managers can leverage digital tools for operational efficiency and visitor engagement. Governments can align policies to support digital transformation. Society can benefit from digital platforms to increase awareness and participation in geoheritage conservation. By addressing the underexplored intersection of digital technologies and geoheritage management, this research bridges gaps in the literature and provides a roadmap for future studies. It emphasizes digitalization as a transformative tool for advancing sustainability and fostering informed, engaged communities.

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1. Introduction

1.1. Background

Geoheritage and geoparks play a crucial role in conserving natural and cultural resources while promoting economic growth, cultural education, and environmental sustainability (Gordon, Crofts, Gray, & Tormey, 2021). Geoheritage refers to geological fea-

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tures of scientific, cultural, aesthetic, or educational significance, while geoparks are designated areas that protect and promote these sites through sustainable development and tourism (Garcia, Queiroz, & Mucivuna, 2022; Gravis, Németh, Twemlow, & Németh, 2020). With increasing urbanization, climate change, and environmental degradation, these valuable landscapes face mounting threats that endanger their longevity and relevance (Pescatore, Bentivenga, & Giano, 2023). As society enters the smart society where technology and human-centered development converge, digitalization presents an opportunity to enhance geoheritage management through innovative solutions such as digital mapping, augmented reality (AR), and smart tourism platforms (Mondejar et al., 2021). In the framework of smart society, where technology and human society co-evolve, digital tools are increasingly integrated into the management of these sites (Rohayati & Abdillah, 2024). Digital tools can enhance conservation efforts, improve visitor experiences, and support sustainable site management while advancing several Sustainable Development Goals (SDGs), particularly SDG 8 (Decent Work and Economic Growth), SDG 11 (Sustainable Cities and Communities), and SDG 15 (Life on Land) (Chen, Shao, Deng, Wang, & Wang, 2023).

Despite the huge potential offered by digitalization, current research on geoheritage and geoparks still lacks coherence. Previous studies frequently ignore the global view of digital adoption in management of geoparks and are usually based on regional cases (Fernández Álvarez, 2019; Bollati, Crosa Lenz, Zanoletti, & Pelfini, 2017; Henriques, Canales, García-Frank, & Gomez-Heras, 2019). While research accepts the geoheritage role in sustainability and development, no systematic analysis has been done on the ways geoheritage is impacted using direct technology (Matshusa, Leonard, & Thomas, 2021). Yet, most of such studies deal with digital applications separately, without offering a theoretical and methodological framework for introducing digital tools into geoheritage and geopark management at an appropriate scale (Chang, Hsu, & Jong, 2020; Fassoulas, Nikolakakis, & Staridas, 2022; Migoń & Pijet-Migoń, 2017). To address these issues, this study builds upon the antecedents, decisions, outcomes-theories, contexts, methods (ADO-TCM) framework, which provides a structured approach to analyze the drivers, decision-making processes, and impacts of digitalization in geoheritage and geoparks (Koi-Akrofi, Aboagye-Darko, Gaisie, & Banaseka, 2023). By merging the case study level with the strategic level, this approach fills the gap between isolated case studies and broader digital adoption understanding that allows research findings to be applied in terms of policies for stakeholders like the governments, tourism operators and conservationists.

The digitalization advancements and trends of geoheritage and geoparks are systematically analyzed through bibliometric and systematic literature review (SLR) mechanism employing ADO-TCM framework. This study researches the key antecedents (physical, political, the economic), the decision-making processes (technology, digital, and governance), and the outcomes (economic value, improved cultural teaching, and environmental change). Finally, this study examines the theoretical foundations of the digitalization in geoheritage, evaluates digitalization at the regional levels, and evaluates the methodological approaches used in earlier geoheritage studies with the purpose of identifying gaps and opportunities for future studies. By integrating the ADO-TCM framework with bibliometric analysis, this research contributes to both theoretical and practical discourse on digitalization in geoheritage. It provides a structured framework for understanding digital transformation in geoheritage and geoparks management, highlights underexplored research areas, and offers insights for policymakers, researchers, and practitioners seeking to leverage digital tools for sustainable development. Additionally, this study bridges technological and managerial perspectives, ensuring a holistic approach that facilitates the scalability and practical application of digital innovations in geoheritage conservation and geotourism.

1.2. Research problem

1.2.1. Research objectives

This study aims to systematically map research trends on digitalization in geoheritage and geoparks, particularly regarding its impact on economic growth, cultural education, and sustainability. In alignment with representation-oriented reviews as stated by Kunisch, Denyer, Bartunek, Menz, & Cardinal, 2023, this study seeks to illustrate the global research landscape by identifying geographical contributions, collaboration patterns, and key knowledge gaps. This approach follows the knowledge-mapping function of systematic reviews, where bibliometric analysis codifies and evaluates scholarly contributions (Yeboah, 2023). The specific objectives of this study are as follows:

(1) examine global trends in the literature on geoheritage and geoparks, focusing on their contribution to economic growth, cultural education, and sustainability;
(2) evaluate the effectiveness of digitalization strategies in geoheritage and geoparks, and assess how these strategies contribute to advancing SDGs;
(3) apply the ADO-TCM framework, exploring its utility in addressing gaps in geoheritage and geoparks research and providing policy-oriented solutions for stakeholders.

1.2.2. Research questions

To guide the systematic literature review and fill the identified research gap, the following research questions will be explored:

(1) What are the key strategies and practices in the digitalization of geoheritage and geoparks that promote economic growth, cultural education, and sustainability?
(2) How do existing studies on geoheritage and geoparks contribute to advancing SDGs, and what are the global implications of these findings?
(3) How can the ADO-TCM framework be applied to enhance the understanding of digitalization's impact on geoheritage and geoparks, and what practical insights can it offer for policy development?

2. Methodology

2.1. Study design

This study employed the SLR and bibliometric analysis to investigate the role of digitalization in geoheritage and geoparks, specifically focusing on its contribution to economic growth, cultural education, and the achievement of SDGs. The SLR was conducted following the structured three-phase methodology outlined by Tranfield, Denyer and Smart (2023), encompassing searching, screening, and analyzing relevant literature. Clear criteria were used to identify eligible studies that guided the research objectives. The methodology developed by Chytis, Eriotis and Mitroulia (2024) was used to conduct bibliometric analysis to assess the productivity, impact, and intellectual structure of the research field. The body of knowledge was analyzed using key bibliometric techniques, i.e., citation analysis and co-occurrence mapping using VOS viewer to discern relationships and trends. Furthermore, the ADO-TCM framework also allowed a structured lens for analysis to study the drivers, strategic decisions, and outcomes of digitalization for geoheritage and geoparks. Using this framework, the study adds two things: (1) a global view into how the digitalization of geoheritage and geoparks integrates into the SDGs, and (2) actionable insights and policy recommendations for the digitalization in the geoheritage and geoparks in order to achieve SDGs. The dual lens framework, which enriches the analytical process with theoretical and context sensitive insights which are pertinent to the global context, was used (Aulia, Afiff, Hati, & Gayatri, 2024).

2.2. Data collection

For this study, data were extracted from the Scopus database, a database that has high-quality indexing and powerful bibliometric tools (Baas, Schotten, Plume, Côté, & Karimi, 2020). While alternative databases such as Web of Science (WoS) and Google Scholar exist, Scopus was chosen due to its structured indexing, high-quality journal selection, and suitability for bibliometric analysis (Thelwall, 2018). Scopus encompasses a broader range of research publications and indexes 97% of the journals available in WoS (Pranckute, 2021). In addition, Scopus offers a full citation analysis and indexing across the disciplines, which is very useful for SLR (Christofi, Vrontis, Thrassou, & Shams, 2019). The inclusion criteria ensured that only relevant studies aligned with the research objectives were considered, while exclusion was based on relevance to the study's scope, publication type, and language. The purpose of the study was to determine key trends and themes around digitalization in geoheritage and geoparks, including the role that it played as a driver of economic, cultural, and sustainability outcomes. Thus, the research string was constructed by carefully selecting terms related to the keywords such as “digitalization,” “geoheritage,” “geopark,” and “sustainability” in order to start the data collection. Furthermore, these terms were further filtered out using geographic and contextual filters to select the articles with global coverage. The overall data collection and analysis process is illustrated in Figure 1, which outlines the research methodology used in this study. For Fig. 2, articles were only searched in subject areas such as Environmental Science, Earth and Planetary Sciences, and Social Sciences, published in English language between 2014 and 2024.

This initial search yielded 240 records, which underwent a systematic screening process guided by the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 guidelines. The PRISMA framework ensured transparency and rigor in the identification, screening, and inclusion of studies, as shown in Fig. 2. During the title and keyword screening, 28 articles were excluded for lacking relevance. A subsequent screening of review papers removed an additional 12 articles that did not align with the study objectives. Abstract screening further excluded 32 articles, leaving 158 articles for full-text review. At this stage, 20 articles were removed due to irrelevance or failure to address digitalization within the geoheritage and geoparks domain.

Ultimately, 138 articles met the inclusion criteria and were subjected to bibliometric analysis. The final selection, illustrated using a PRISMA flow diagram, ensured a comprehensive and high-quality dataset. This dataset allowed for an in-depth exploration of the intersections between digitalization and geoheritage, particularly in advancing economic, cultural, and SDG-related objectives. The systematic approach enabled the identification of research gaps and actionable insights to guide stakeholders and future research in this evolving field.

3. Results and discussion

3.1. Performance analysis

Over the past decade, research publications on geoheritage and geoparks have significantly increased, particularly in the areas of geotourism, sustainability, and digital transformation. These studies highlight the contributions of geoheritage to economic growth, education, and the SDGs. Fig. 3 presents the publication trends from 2014 to 2024, based on the 138 articles analyzed in this study, illustrating the growing academic focus on digitalization in geoheritage and geopark management. The data reveal a steady but modest publication rate between 2014 and 2018, with annual outputs ranging from 5 to 8 articles (3.62%–5.80%). A significant rise occurred in 2019, with 13 articles (9.42%), reflecting the increasing global emphasis on digital tools for heritage conservation and sustainable tourism development. The momentum continued in 2020 and 2021, with 15 articles each year (10.87%), despite temporary fluctuations. Notably, from 2022 onward, publications surged, reaching a peak of 23 articles in both 2023 and 2024 (16.67% for each). This trend indicated a sustained and growing scholarly interest in the role of digitalization for geoheritage conservation, geotourism promotion, and geopark management strategies.

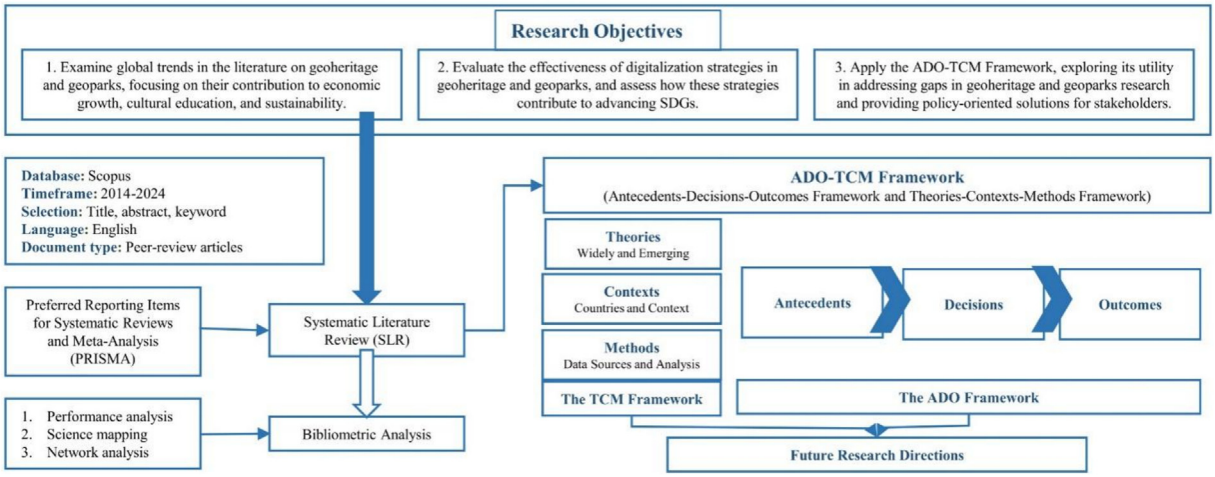

Fig. 1. Research methodology.

Among the journals listed in Table 1, *Geoheritage* led with 35 publications and a total of 620 citations, demonstrating its dominant role in advancing research on geoheritage conservation and digital transformation in geoparks. *Geosciences* followed with 12 publications and 212 citations, reflecting its significant contribution to the field. The *International Journal of Geoheritage and Parks* had 11 publications, highlighting its specialized focus on this research domain. Citation analysis identified *Sustainability* as another key contributor, with an *h*-index of 169, 5 publications, and 119 citations, emphasizing its impact on sustainability, digitalization, and cultural education. Table 2 showcases the top 10 influential journals, presenting their cumulative impact through metrics such as *h*-index, total citations, and publication count, underscoring their importance in shaping interdisciplinary research on geoheritage, geoparks, and environmental sustainability in the digital era.

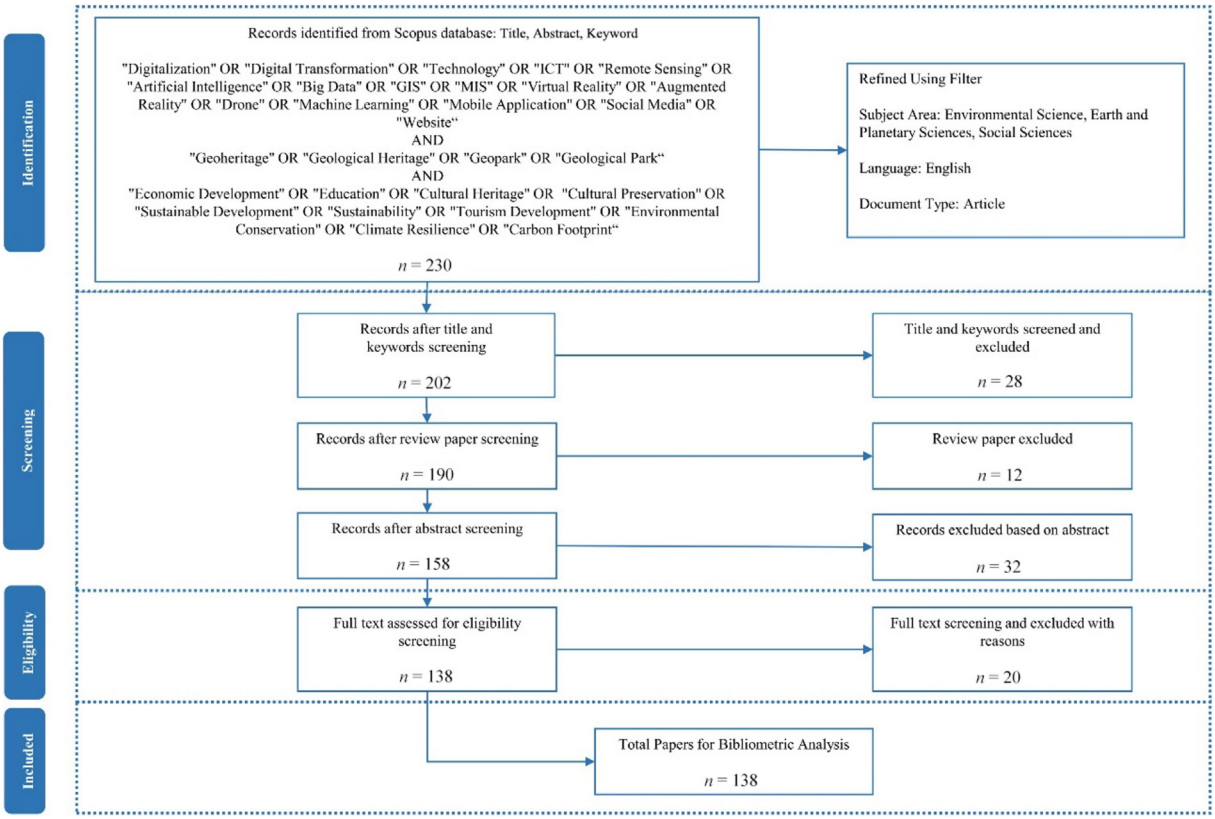

Fig. 2. PRISMA diagram.

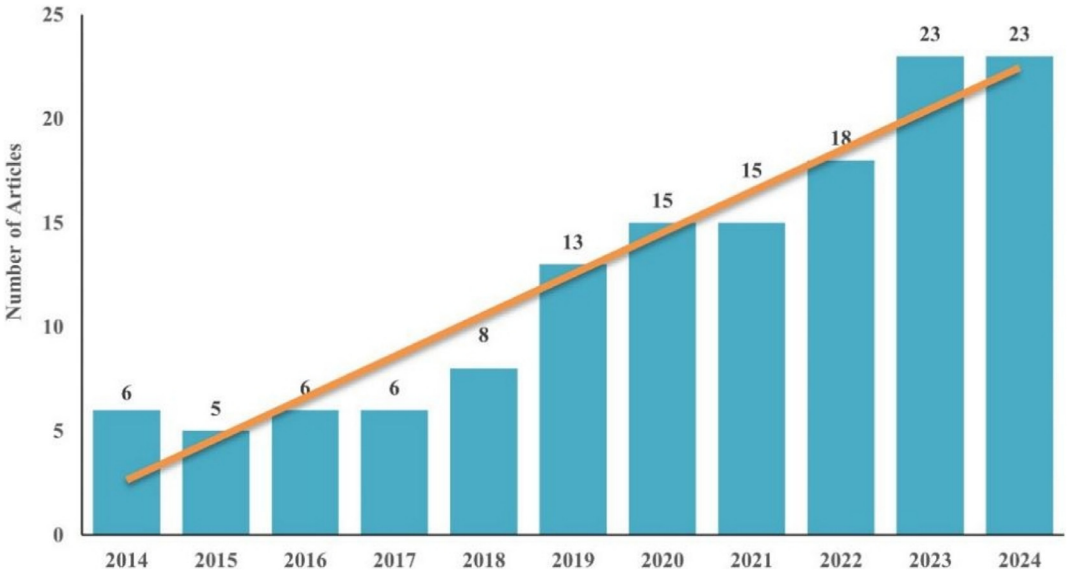

Fig. 3. Number of articles used in this research.

The most cited article by Chang et al. (2020) led with an impressive 147 citations, reflecting its significant contribution to the discourse on virtual reality (VR) learning and geoeducation. Following this, Migoń and Pijet-Migoń (2017) had garnered 111 citations, highlighting their impact on the management and conservation of viewpoint geosites for education and tourism. Another influential work included Bétard and Peulvast (2019) with 73 citations, which proposed an integrated GIS-based approach for mapping geodiversity hotspots to support geoconservation efforts. Table 3 provides a comprehensive overview of the top 10 most influential articles, underscoring their pivotal role in advancing research on digitalization, geoheritage, geoparks, and sustainable development.

In line with the objective of this paper, this analysis mapped the research landscape on digitalization in geoheritage and geoparks. One crucial aspect of this mapping was understanding the geographical distribution of research contributions, which provided insights into regional research strengths, collaboration patterns, and potential knowledge gaps. Table 4 presents the leading countries contributing to geoheritage and geoparks research, highlighting significant global representation. Italy emerged as the dominant contributor with 22 articles, of which 21 were single-country publications (SCP) and only 1 involved multiple-country publication (MCP), resulting in a low MCP ratio of 0.045. This suggested that research in Italy was primarily driven by domestic efforts rather than international partnerships. Similarly, Spain (14 articles, MCP ratio of 0.071) and China (10 articles, MCP ratio of 0.100) exhibited a strong national focus, with limited international collaborations. Meanwhile smaller contributors such as Czech Republic, Ecuador, Ethiopia, and Cyprus stood out as countries with a relatively high international collaboration rate (MCP ratio of 1.000), despite contributing fewer total publications, highlighting their strong international engagement.

While Italy, Spain, and China led in total publications, their low MCP ratios highlighted the need for greater international collaboration to enrich research diversity and improved the quality of geoheritage and geopark management studies. Strengthening cross-border partnerships could facilitate knowledge exchange, integrate diverse methodological approaches, and promote best practices in conservation and sustainable tourism. At the same time, expanding research in underrepresented regions such as the USA, Canada, and India was crucial, given their vast geological and cultural heritage. Despite their potential, these countries had minimal contributions to the field, creating a geographic gap in the literature. Future studies should focus on exploring

Table 1
Most impactful journals.

Sources (journals)	*h*-index	CiteScore	Total citations	Number of publications
Geoheritage	44	5.1	620	35
Geosciences	50	5.3	212	12
International Journal of Geoheritage and Parks	19	6.7	61	11
Land	54	4.9	108	10
Sustainability	169	6.8	119	5
Resources	54	7.2	36	5
Rendiconti Online Societa Geologica Italiana	20	0.8	21	4
Journal of Mountain Science	55	4.2	45	3
Minerals	58	4.1	72	3
Open GeoSciences	38	3.1	22	2

Table 2
Most influential publications.

Title	Year	Total citations	Citations per Year
Integration of the peer assessment approach with a virtual reality design system for learning earth science	2020	147	29
Viewpoint geosites—Values, conservation and management issues	2017	111	14
Geodiversity hotspots: Concept, method and cartographic application for geoconservation purposes at a regional scale	2019	73	12
GeoGuides, Urban Geotourism Offer powered by mobile application technology	2018	70	10
GIS-based integrated evaluation of environmentally sensitive areas (ESAs) for land use planning in Langkawi, Malaysia	2016	67	7
Geomorphodiversity index: Quantifying the diversity of landforms and physical landscape	2017	63	8
Chronicles and geoheritage of the ancient Roman city of Pompeiopolis: a landscape plan	2018	60	14
Geotourism—Examining tools for sustainable development	2021	55	5
Using geoinformatics and geomorphometrics to quantify the geodiversity of Crete, Greece	2016	49	7
TOURinSTONES: A free mobile application for promoting geological heritage in the city of Torino (NW Italy)	2019	43	8

geoheritage in these regions, fostering international cooperation to ensure more comprehensive and globally inclusive research on geopark management and conservation strategies.

3.2. Science mapping

For this study, science mapping was employed to uncover connections between key elements in geoheritage and geoparks research, focusing on their contributions to economic growth, cultural education, and the advancement of the SDGs (Y. Li & Wang,

Table 3
Literature matrix of influential articles.

Authors	Objective	Research method	Findings	Effect
Chang et al. (2020)	To empirically examine the effectiveness of integrating peer assessment with VR design activities in enhancing students' environmental awareness and earth science knowledge in a geological park learning context	Analysis of covariance (ANCOVA)	Students using the VR design activity with peer assessment performed significantly better in knowledge acquisition, motivation, and cognitive skills	Positive
Migoń and Pijet-Migoń (2017)	To explore the significance, conservation, and management issues of viewpoint geosites and their role in landscape interpretation and geoeducation	Thematic analysis	Viewpoint geosites are valuable for education and tourism, but their management must balance conservation efforts with accessibility and infrastructure development	Mixed
Migoń and Pijet-Migoń (2017)	To propose and apply an integrated GIS-based method to identify and map geodiversity hotspots by quantifying geodiversity and threat indices, aiming to support geoconservation efforts	GIS-based spatial analysis Cartographic methods	The study successfully identifies geodiversity hotspots, but many faces significant threats, particularly in Ceará State, Brazil	Mixed
Pica et al. (2018)	To investigate the role of mobile applications in promoting urban geotourism by integrating geoscientific knowledge with cultural and geological heritage	Content analysis	Mobile applications enhance geotourism experiences, facilitate knowledge transfer, and increase public engagement with urban geological heritage	Positive
Leman, Ramli and Khirotdin (2016)	To assess environmental sensitivity and land use planning strategies in Langkawi using GIS-based evaluation models	GIS-based spatial analysis Analytic hierarchy process (AHP)	The GIS-based evaluation identified highly sensitive areas, supporting conservation efforts, but challenges remain in balancing tourism and environmental protection	Mixed
Melelli, Vergari, Liucci and Del Monte (2017)	To develop a quantitative geomorphodiversity index to assess and promote geological heritage using digital elevation models	GIS-based spatial analysis Digital elevation models (DEMs)	The geomorphodiversity index effectively identifies and validates geologically diverse areas for conservation and promotion	Positive
Cetin, Onac, Sevik, Canturk and Akpinar (2018)	To evaluate the recreational and tourism potential of Pompeiopolis and propose strategies for sustainable landscape planning	Landscape evaluation modeling using the Gülez formula Observation-study analysis Oral interviews	Pompeiopolis has high recreational and ecotourism potential, requiring improved management and planning for long-term sustainability	Positive
Frey (2021)	To examine geotourism as a sustainable development tool by analyzing infrastructure, local participation, and geosite assessment in multiple UNESCO Global Geoparks	Case study approach Document analysis	Community-led approaches foster sustainable tourism, education, and cultural conservation	Positive
Argyriou, Sarris and Teeuw (2016)	To develop a GIS-based geodiversity index for Crete by analyzing geomorphometric, geological, and climatic factors	GIS-based spatial analysis	Western Crete has high geodiversity due to complex geological processes, supporting conservation and natural resource management	Positive
Gambino et al. (2019)	To explore the role of mobile applications in promoting geological heritage in urban tourism.	Content analysis	Mobile apps facilitate geotourism engagement without physical impact	Positive

Table 4
Top countries by articles.

Country/Region	Articles	SCP	MCP	Frequency	MCP ratio
		Country			
Italy	22	21	1	0.151	0.045
Spain	14	13	1	0.096	0.071
China	10	9	1	0.068	0.100
Greece	8	7	1	0.055	0.125
Turkey	6	6	0	0.041	0.000
Brazil	6	5	1	0.041	0.167
Indonesia	6	5	1	0.041	0.167
New Zealand	5	5	0	0.034	0.000
Portugal	5	4	1	0.034	0.200
Morocco	4	4	0	0.027	0.000
Vietnam	3	3	0	0.021	0.000
Switzerland	3	2	1	0.021	0.333
Costa Rica	3	1	2	0.021	0.667
Australia	2	2	0	0.014	0.000
Poland	2	2	0	0.014	0.000
Saudi Arabia	2	2	0	0.014	0.000
USA	2	2	0	0.014	0.000
Cameroon	2	1	1	0.014	0.500
Germany	2	1	1	0.014	0.500
Mexico	2	1	1	0.014	0.500
Czech Republic	2	0	2	0.014	1.000
Ecuador	2	0	2	0.014	1.000
Ethiopia	2	0	2	0.014	1.000
Angola	1	1	0	0.007	0.000
Argentina	1	1	0	0.007	0.000
Canada	1	1	0	0.007	0.000
France	1	1	0	0.007	0.000
Hungary	1	1	0	0.007	0.000
India	1	1	0	0.007	0.000
Iraq	1	1	0	0.007	0.000
Ireland	1	1	0	0.007	0.000
Kazakhstan	1	1	0	0.007	0.000
Malaysia	1	1	0	0.007	0.000
Russia	1	1	0	0.007	0.000
Serbia	1	1	0	0.007	0.000
South Africa	1	1	0	0.007	0.000
South Korea	1	1	0	0.007	0.000
Ukraine	1	1	0	0.007	0.000
Cyprus	1	0	1	0.007	1.000
		Region			
Global	11	11	0	0.075	0.000
Europe	2	2	0	0.014	0.000
Central America	1	1	0	0.007	0.000
Latin America	1	1	0	0.007	0.000

2023). This involved co-word analysis, which identified frequently co-occurring keywords to reveal the intellectual structure of the field, and thematic analysis, which organized research topics into thematic clusters to highlight dominant trends and emerging areas of interest (Dwivedi, Nerur, & Balijepally, 2023). A cluster analysis of keywords commonly used by authors in titles and abstracts was conducted to identify prominent research areas. These keywords were extracted and aggregated, then visualized using VOS viewer software, which grouped them into thematic clusters based on their co-occurrence in the selected articles (Kirby, 2023). A minimum occurrence threshold of 10 was set to generate a co-occurrence map (Fig. 4), unveiling three thematic clusters.

The first cluster (red), "Geoheritage Management and Digital Conservation Strategies," focused on the systematic assessment, preservation, and promotion of cultural and natural heritage sites through digital tools and data-driven approaches. Keywords such as "geodiversity," "cultural heritage," "management," and "visitor" highlighted the growing role of technology in identifying, mapping, and monitoring geosites while ensuring long-term conservation efforts. The use of GIS-based methodologies, digital databases, and smart monitoring tools enhanced decision-making processes for sustainable geoheritage management. Additionally, this cluster emphasized the importance of promoting geoheritage through digital campaigns, virtual storytelling, and interactive platforms to increase public awareness and engagement in conservation initiatives. In terms of combining technological development with determined practices based on the community's cultural knowledge, it was clearly an advantage because it brought together the technology for integration by the policymakers and local communities.

The second cluster (green), "Digital Technologies and Smart Solutions in Geoheritage and Geoparks," explained how digitalization could improve the assessment and monitoring, and even the enrichment of geoheritage experiences. Keywords such as

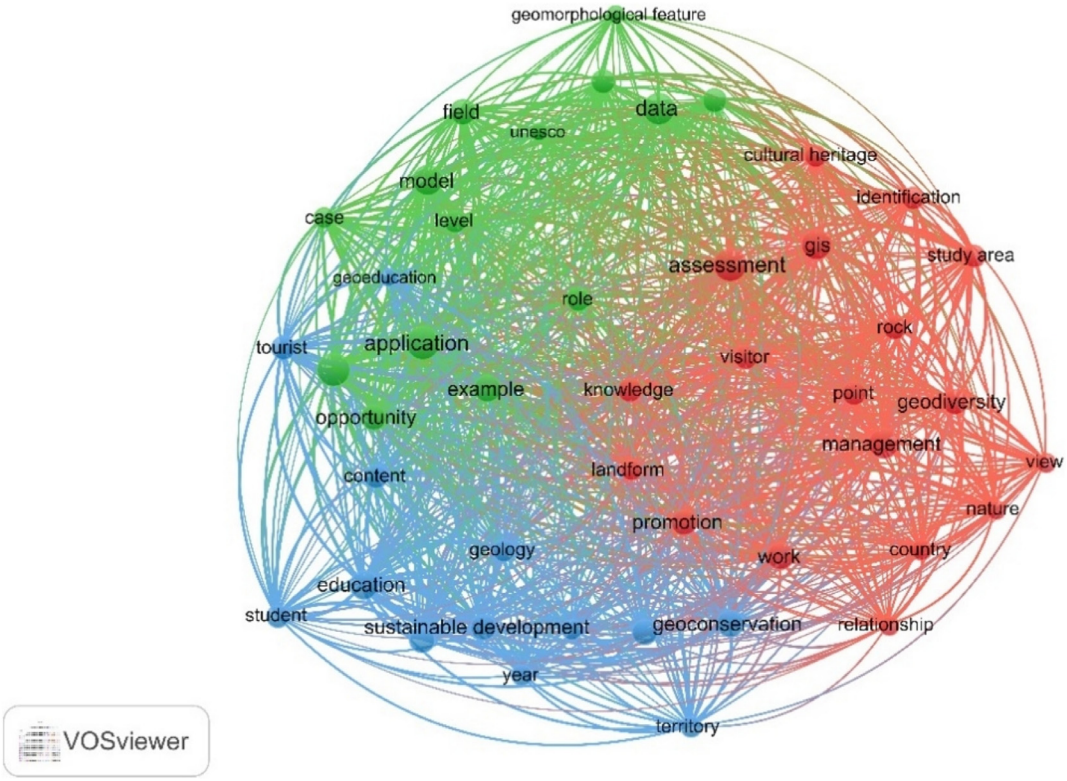

Fig. 4. Co-word analysis.

"data," "application," "model," "technology," and "UNESCO" reflected the increasing reliance on smart solutions for geotourism and conservation planning. By using geospatial analysis, AI mapping, immersive digital tools such as AR and VR, we could address issues of the less engaging visitor experience as well as provide ways for researchers and managers to make informed decisions on site conservation. This cluster highlighted the importance of digitalization in overcoming the divide between science and practice in relation to geoparks, proposing novel ways of dealing with geoparks. It also examined how digital archives and databases provided access to geoheritage information, preventing it from falling into oblivion.

The third cluster (blue), "Geoeducation, Digital Learning, and Sustainable Development in Geoparks," explored the implications of digital education to promote awareness, engagement and sustainable development in geoparks. Keywords such as "education," "student," "geoconservation," "territory," "tourist," and "sustainable development" indicated the growing importance of integrating digital learning tools in geoconservation efforts. The interaction with geoheritage and its importance were offered by the e-learning platforms, online training modules, and the interactive virtual simulations for students, researchers, and visitors. It was aslo part of this cluster, the role of digital outreach programs to support post-tourism environmental stewardship and sustainable tourism. Bringing technology into the geoeducation capability of geoparks could promote scientific literacy, support local communities, and promote responsible tourism practices that were in accordance with long term conservation goals. Digital education thus served as a bridge between scientific research and public engagement, ensuring that knowledge about geoheritage was effectively disseminated and applied.

3.3. Network analysis

Fig. 5 shows the network analysis of 12 clusters. It reveals six dominant ones—red, green, dark blue, yellow, purple, and light blue—that collectively illustrate how digitalization is transforming geoheritage and geoparks, driving advancements in visualization, accessibility, conservation, and geotourism development. These clusters highlight the contributions of leading authors whose research advances knowledge in their respective areas.

The red cluster focused on IT applications and digital tools for geoheritage promotion and geotourism in geoparks. Notably, Frey (2021) led with 55 citations and explored geotourism as a tool for sustainable development, while Leman et al. (2016) contributed GIS-based methodologies for land-use planning in Malaysia. Henriques et al. (2019) stated accessibility as the main theme referred to in a geopark, consistent with the sector's growing need for inclusive tourism. The green cluster was centered on geoheritage site assessments and geotourism development strategies. Beraaouz et al. (2019) led with 35 citations analyzing Morocco's Draa Valley to promote sustainable geotourism, while Quesada-Román, Zangmo and Pérez-Umaña (2020) provided comparative assessments of volcanic geomorphosites across multiple countries. Ivanović, Lukić, Milentijević, Bojović and

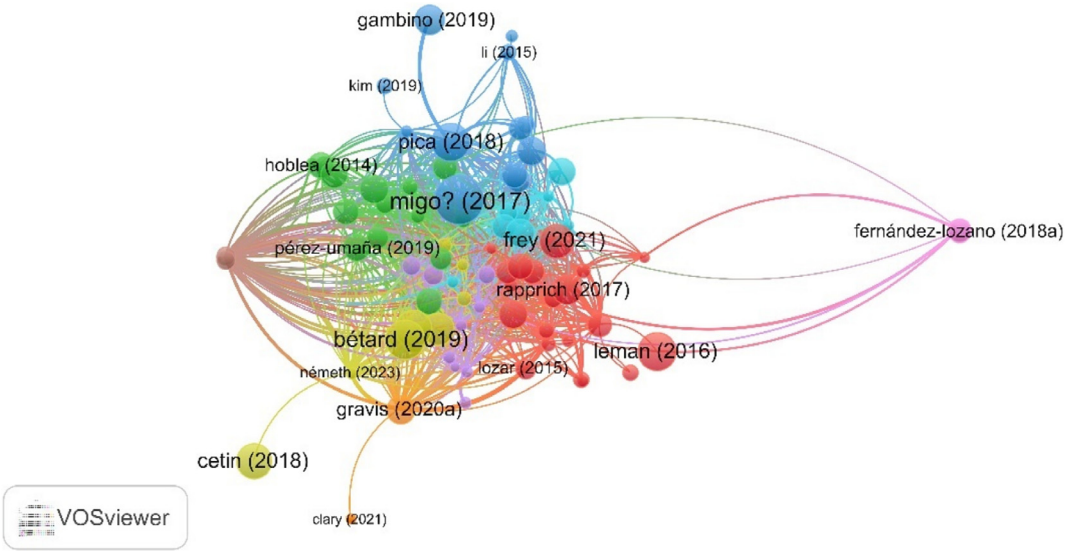

Fig. 5. Co-citation network analysis.

Valjarević (2023) applied GIS-based evaluations to identify geotourism potential in various landscapes, reinforcing the role of spatial analysis in geoheritage management.

The dark blue cluster highlighted technological advancements in geovisualization for geotourism and geoconservation. This cluster of research was based upon the rise in use of virtual reality, 3D visualizations, and interactive web mapping in the education and tourism of geoheritage. Migoń and Pijet-Migoń (2017) led this cluster with 111 citations of their work on viewpoint geosites, focusing on conservation and management strategies. Pica et al. (2018) followed to explore the mobile applications for urban geotourism, while Gambino et al. (2019) introduced TOURinSTONES, an app for promoting geological heritage in Italy. The yellow cluster emphasized geodiversity assessment and geoconservation methodologies, collectively advanced methodologies for geodiversity mapping and conservation planning. Bétard and Peulvast (2019) contributed significantly to this theme with 73 citations of their work on geodiversity hotspots, while Melelli et al. (2017) introduced a geomorphodiversity index for quantifying landscape diversity and Cetin et al. (2018) examined the geoheritage of Pompeiopolis, integrating historical and geological perspectives.

The purple cluster highlighted the need for integrated approaches in preserving both geological and cultural heritage. Szepesi et al. (2020) led this cluster with 19 citations, who examined geoheritage elements in Hungary's Tokaj Mountains. Williams and McHenry (2021) applied geographic information technology (GIT) to assess geoconservation inventories. The last (light blue) cluster was devoted to AR and 3D technologies' role in the geoheritage education and tourism. Martínez-Graña, González-Delgado, Pallarés, Goy and Llovera (2014) led this theme with 37 citations while observing the AR applications for promoting geodiversity in Spain's Arosa Estuary. Additional studies by the same author explored 3D virtual itineraries for natural parks, showcasing the potential of digital tools in enhancing visitor engagement and educational outreach (Martínez-Graña et al., 2019).

3.4. ADO-TCM framework

This section applied the ADO-TCM framework to explore the role of digitalization in geoheritage and geoparks, as shown in Fig. 6. This framework provided a holistic approach for evaluating factors that led to digitalization antecedents (A), decisions (D), outcomes (O), theories (T), contexts (C), and methods (M) that were used and found from bibliometric data. Through this approach, the paper aimed to understand the potential of digitalization to accelerate economic growth, improve cultural education, and support the achievement of the SDGs.

3.4.1. Antecedents (A)

In this section, the paper examined the antecedents influencing the adoption and integration of digitalization within geoheritage and geopark management, focusing on three key subthemes: (1) technological innovations and digital transformation, (2) cultural and economic drivers, (3) environmental pressures, urbanization, and scientific research.

3.4.1.1. Technological innovations and digital transformation. As shown in Table 5, the analysis highlighted that digitalization and technological advancements served as key antecedents for the transformation of geoheritage management (Hoblea, Delannoy, Jaillet, Ployon, & Sadier, 2014). Innovations such as GIS, remote sensing, UAVs, LiDAR, VR, and AR played a pivotal role in geoconservation by enhancing data collection, visualization, and decision-making processes (Fernández-Lozano et al., 2018; Martínez-Graña et al., 2017). Furthermore, digital tools had been integrated to geoconservation efforts to increase the access to the

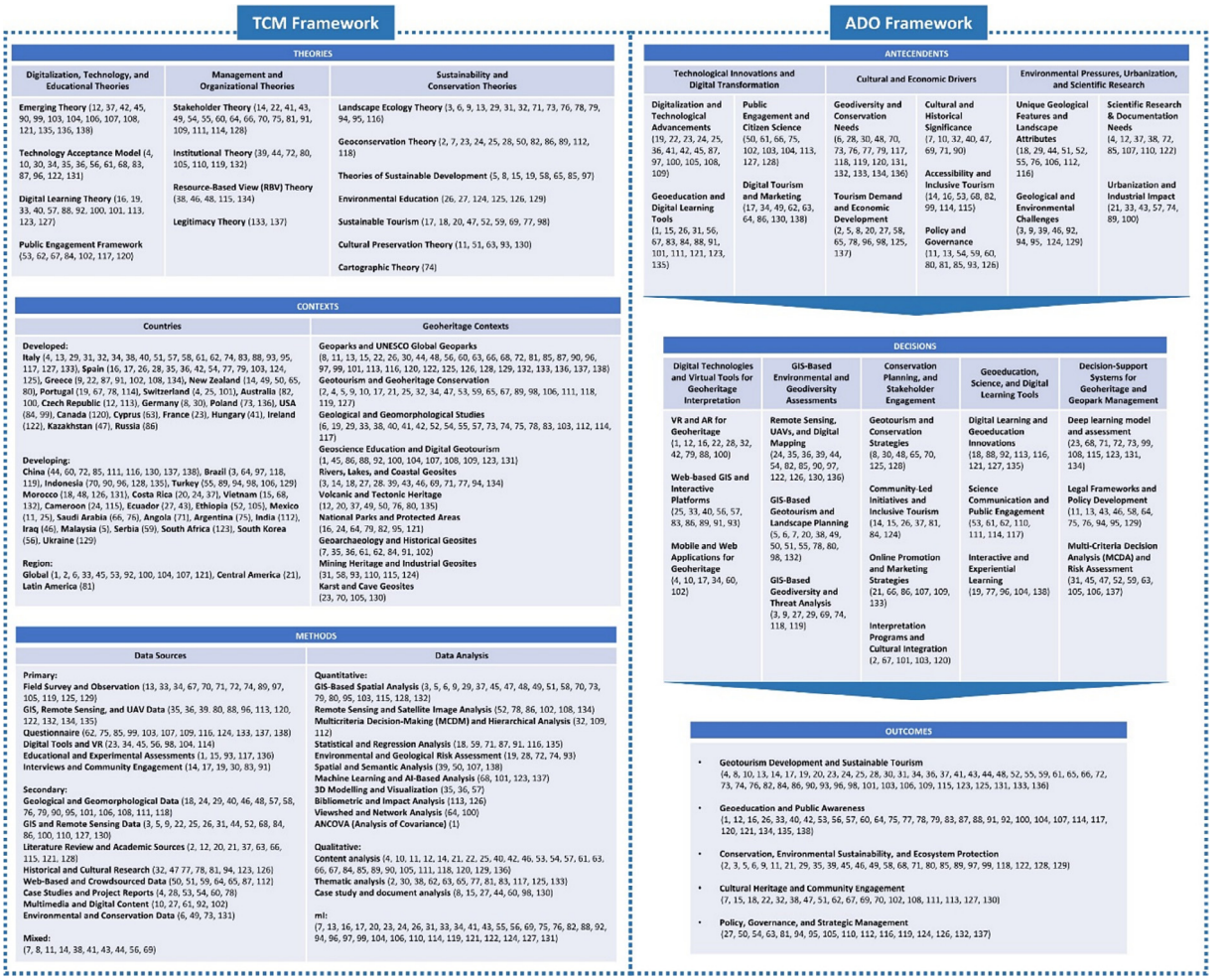

Fig. 6. Research based on the ADO-TCM framework.

Table 5
Technological innovations and digital transformation antecedents.

Antecedents	Sub-factor	References	Association with geoheritage and geoparks improvement
Digitalization and technological advancements	Digital technology in geoconservation	Fassoulas et al., 2022; Hoblea et al., 2014; Quesada-Román & Pérez-Umaña, 2020	Positive
	Advances in GIS, remote sensing, UAVs, LiDAR, VR, and AR	Fernández-Lozano et al., 2018; Luan & Wang, 2023; Martínez-Graña et al., 2017; Martínez-Graña, Serrano, et al., 2017	Positive
Geoeducation and digital learning tools	AR/VR for immersive learning in geology	Chang et al., 2020; Chin & Wang, 2024; Rodríguez, Sevilla, Obeso, & Herrera, 2022	Positive
	Challenges in physical geological field trips	Kim & Lim, 2019; Maloney et al., 2023; Meini, Di Felice, & Petrella, 2018	Positive
	Digital learning tools and ministerial education policies	Fernández Álvarez, 2019; Clary, 2021; Pelfini et al., 2019	Positive
Public engagement and citizen science	Crowdsourced data and digital tools for public participation	Keskin Citiroglu & Arca, 2023; Nakarmi et al., 2023; Potsikas, Prouska, Efthimiou, Plakitsi, & Kornelaki, 2023	Positive
	Circular economy awareness, environmental concerns, and policy gaps	Coronato & Schwarz, 2022; Garcia et al., 2022; Louz, Rais, Ait Barka, Nadem, & Barakat, 2022	Mixed
Digital tourism and marketing	Social media and digital mapping tools	Fox, Chamberlain, Lindquist, & Van Berkel, 2022; Helmi et al., 2024; Németh, Németh, & Procter, 2021	Positive
	Media popularity and geotourism demand	Lugeri, Farabollini, Greco, & Amadio, 2015; Martínez-Graña et al., 2017; Molokáč, Kornecká, Pavolová, Bakalár, & Jesenský, 2023	Mixed

geological sites, remote monitoring and consolidation of geoconservation policy (Maloney et al., 2023). Advances in digital education tools further contributed by addressing challenges in physical geological field trips, providing immersive learning experiences through AR/VR and aligning with ministerial education policies to promote digital learning in geoheritage studies (Pelfini et al., 2019).

Similarly, the rise of digital tourism and marketing had reshaped the way geoheritage sites were promoted and experienced (Fassoulas et al., 2022). The increasing popularity of social media platforms and digital mapping tools had heightened interest in geotourism, allowing for broader outreach and enhanced visitor engagement (Fox et al., 2022). Public engagement in geoconservation had also benefited from digital innovations, as citizen science initiatives leveraged crowdsourced data and digital tools to foster community participation in conservation efforts (Helmi et al., 2024). However, policy gaps and varying levels of environmental awareness remained challenges that must be addressed to maximize the impact of digital transformation in geoheritage (Ivanović et al., 2023). Bridging these gaps through targeted education, strategic policymaking, and increased public involvement could enhance the effectiveness of digital initiatives, ensuring long-term sustainability in geoheritage management (Nakarmi et al., 2023).

3.4.1.2. Cultural and economic drivers. As shown in Table 6, cultural and economic drivers played a crucial role in shaping geoconservation and sustainable geotourism development. Geodiversity and conservation needs remained central to geoheritage management, as challenges in geological mapping and geodiversity assessments impacted conservation strategies (Carrión-Mero, Dueñas-Tovar, Jaya-Montalvo, Berrezueta, & Jiménez-Orellana, 2022). While geodiversity held significant tourism potential, the lack of structured conservation policies often hindered the sustainable development of these sites (Gravis et al., 2020). Similarly, paleontological and geological heritage preservation was essential for maintaining the scientific and cultural value of these locations, ensuring that they remained protected for future generations (Bisconti et al., 2023). Integrating conservation efforts with sustainable tourism development could bridge the gap between scientific preservation and economic benefits, fostering long-term sustainability in geoheritage management (Henriques et al., 2019).

The cultural and historical significance of geoheritage sites further strengthened their value, as many geological formations held deep connections to historical and cultural narratives (Cetin et al., 2018). Conservation efforts increasingly integrated both cultural and geological heritage to create immersive tourism experiences, supporting local economies and preserving intangible cultural elements, such as transhumance practices and historical sites ( ). Additionally, geological formations often served as key architectural and cultural landmarks, reinforcing their importance in historical and contemporary urban development (Marescotti et al., 2018). However, accessibility remained a pressing issue, as the demand for inclusive tourism policies and disability-friendly initiatives continued to grow (Gambino et al., 2019). Inadequate protective legislation, coupled with a lack of sustainable tourism advocacy, limited the potential of geotourism to serve diverse audiences, highlighting the need for inclusive policies that enhanced accessibility and engagement (Németh & Németh, 2023).

Beyond cultural considerations, economic growth and governance structures were pivotal in the expansion of geotourism and geoconservation (Frey, 2021). The increasing interest in geotourism had driven infrastructure investments and UNESCO recognition efforts, yet the need for sustainable infrastructure in geoparks remained a challenge (Ballesteros et al., 2022). Strengthening governance frameworks was essential, as structured geopark management ensured long-term sustainability while addressing policy gaps in geoconservation (Rosado-González et al., 2023). The integration of SDGs and community engagement into policy-

Table 6
Cultural and economic driver's antecedents.

Antecedents	Sub-factor	References	Association with geoheritage and geoparks improvement
Geodiversity and conservation needs	Geodiversity assessment and geological mapping challenges	Carrión-Mero et al., 2022; Haryono, Reinhart, Hakim, Sunkar, & Setiawan, 2022; Melelli et al., 2017	Positive
	Palaeontological and geological heritage preservation	Bisconti et al., 2023; Louz et al., 2022; Scarsi, Crispini, Malatesta, Spagnolo, & Capponi, 2019	Positive
Tourism demand and economic development	Economic growth, tourism expansion, and UNESCO recognition	Henriques & dos Reis, 2021; Leman et al., 2016; Pérez-Umaña et al., 2019	Positive
	Need for sustainable infrastructure in geoparks	Frey, 2021; Geralis, 2020; Migoń & Pijet-Migoń, 2017	Mixed
Cultural and historical significance	Integration of cultural and geological heritage in conservation	Cetin et al., 2018; Marescotti et al., 2018; Szepesi et al., 2020	Positive
	Geological formations with cultural and architectural significance	Gambino et al., 2019; Lopes, Ramos, Gomes, & Ussombo, 2019; Piniñska et al., 2014	Positive
Accessibility and inclusive tourism	Inclusive tourism policies and disability-friendly initiatives	Gambino et al., 2019; Gravis et al., 2020; Németh & Németh, 2023	Positive
	Demand for accessible geoscientific knowledge	Henriques et al., 2019; Henriques & dos Reis, 2021	Mixed
Policy and governance	Need for structured geopark management	Ballesteros et al., 2022; Q. Li et al., 2015; Rosado-González et al., 2023	Positive
	Sustainable development goals and community engagement	Antoniou et al., 2023; Rosado-González et al., 2023	Positive

making further reinforced the role of economic and regulatory mechanisms in balancing conservation with tourism-driven economic benefits (Antoniou et al., 2023). These factors collectively highlighted the intersection of cultural, economic, and governance dynamics in advancing sustainable geotourism and geoconservation strategies.

3.4.1.3. Environmental pressures, urbanization, and scientific research. As shown in Table 7, environmental pressures, urbanization, and scientific research acted as significant antecedents influencing geoconservation and sustainable geoheritage management. Geological and environmental challenges such as human activities, climate change, and groundwater depletion posed serious threats to geological stability and conservation efforts (Argyriou et al., 2016). Increasing industrial activities and land-use changes contributed to habitat degradation, which necessitated more comprehensive conservation planning strategies (Yürür, Saein, & Kaygısız, 2019). Furthermore, the growing frequency of extreme climate events intensified the risks of erosion, landslides, and other geological instabilities, requiring a more proactive approach to geoconservation (Beraaouz et al., 2019). The solution to these challenges required multiple stakeholders and a policy-driven and tech-enhanced solution which addressed geoheritage site needs for the long term (Ansori, Warmada, Setiawan, & Yogaswara, 2023).

Research in the field of science and technology had a significant role to play in reducing the environmental pressure and in conserving geoheritage (Long, 2016). The availability of research and geoconservation technologies—such as improved geospatial mapping, remote sensing, and digital databases—could significantly enhance conservation inventories and documentation efforts (Lansigu et al., 2014). Fossils and other geological formations discovered by organizations, provided scientific and educational value to geoheritage, therefore, structured research and documentation became essential so that these natural resources would be preserved (Portal, 2023). Geological landscapes, whether through geological activity, geothermal features or a wide variety of each of these, were yet another indicator that the sites needed better management and protection policies that would additionally to the uniqueness of the sites (Zhu et al., 2023). As scientific research advanced, integrating digital tools such as GIS and AI-driven analysis could facilitate better monitoring and decision-making in geoheritage conservation (Ballesteros et al., 2022).

Despite these advancements, urbanization and industrial expansion presented growing concerns for geoconservation efforts (Ansori et al., 2023). Inevitably, though, rapid urban development tended to result in the loss of geological awareness; most sites of significance were overlooked, recorded in a capacity that was at best only dormant, or even encroached upon by infrastructure projects (Geralis, 2020). Other risks included industrial activities, especially for resource exploitation and their negative impacts on landscape degradation and destroying fragile ecosystems (Marescotti et al., 2018). To overcome these challenges, structure geoconservation policies and city planning process should be fortified to incorporate some economic growth and environmental preservation (Pica et al., 2018). Sustainable development strategies integrating geoheritage conservation with growth and expansion of artificial built environmental systems could guarantee protection of geological sites while bringing economic and educational opportunities to local communities (Sansò et al., 2015). By fostering greater awareness and regulatory oversight, policymakers could help bridge the gap between urbanization and environmental sustainability, promoting long-term resilience in geoheritage management (Yürür et al., 2019).

3.4.2. Decisions (D)

In this section, we examined the decision-making processes for digitalization of geoheritage and geoparks management in terms of five key domains which corresponded to digital technologies, GIS-based assessments, conservation planning, geoeducation, and decision-support systems. These domains reflected the decisions that managerial teams made in adopting and implementing strategies that accelerated economic growth, cultural education, and advancements toward the SDGs.

Table 7
Environmental pressures, urbanization, and scientific research antecedents.

Antecedents	Sub-factor	References	Association with geoheritage and geoparks improvement
Unique geological features and landscape attributes	Geothermal activity and geological uniqueness	Ferrando, Faccini, Paliaga, & Coratza, 2021; Lansigu, Bosse-Lansigu, & Le Hebel, 2014; Vereb, van Wyk de Vries, Hagos, & Karátson, 2020	Mixed
	Scenic landscapes and need for improved management	Ansori et al., 2023; Beraaouz et al., 2019; Zhu, Pang, & Zhou, 2023	Positive
Geological and environmental challenges	Human activities and environmental threats	Bétard & Peulvast, 2019; Bruno et al., 2020; Marescotti et al., 2018	Mixed
	Climate change and groundwater depletion	Argyriou et al., 2016; Awadh, Al-Sulttani, & Yaseen, 2022; Melelli, Palombo, & Nazzareni, 2023	Positive
Scientific research and documentation needs	Need for improved geoconservation inventories and databases	Bollati et al., 2017; Portal, 2023; Sansò, Margiotta, Mastronuzzi, & Vitale, 2015	Positive
	Scientific geological research and fossil discoveries	Long, 2016; Nunes, Henriques, Dias, & Janeiro, 2022; Pica et al., 2018	Positive
Urbanization and industrial Impact	Rapid urbanization and lack of geological awareness	Ansori et al., 2023; Martin, 2014; Yürür et al., 2019	Positive
	Industrial expansion and resource exploitation	Careddu, Di Capua, & Siotto, 2019; Morante-Carballo et al., 2022; Quesada-Román et al., 2022	Positive

3.4.2.1. Digital technologies and virtual tools for geoheritage interpretation. The integration of VR and AR technologies in geoheritage interpretation had transformed the way visitors engaged with geological sites, offering immersive and interactive experiences that enhanced learning and accessibility (Chang et al., 2020). Web-based GIS and interactive platforms further supported this digital transformation by enabling real-time mapping, virtual site explorations, and geospatial data visualization for research and education (Fassoulas et al., 2022). Additionally, mobile and web applications gave access to the tourists, researchers, and educators to contribute with the tools such as self-guided tours, augmented reality overlays, and gamified learning experiences (Migoń & Pijet-Migoń, 2017). The digital advancements not only changed not only the way publics engaged with geoheritage but also increased conservation awareness and knowledge dissemination of geoheritage, so that geoheritage could be seen, heard and protected in the digital age (Quesada-Román et al., 2022).

3.4.2.2. GIS-based environmental and geodiversity assessments. Remote sensing, UAVs, and digital mapping had significantly improved the accuracy and boundary and efficiency of environmental monitoring and geodiversity assessment by allowing for real time gathering and analysis of data in order to assist in conservation planning (Bruno et al., 2020). GIS-based geotourism and landscape planning provided additional spatial insights into the visitor patterns, site accessibility, and ecological impact across the two cases improving the provisions for sustainable tourism management and to ensure that tourism development was in line with the conservation goals (Melelli et al., 2017). GIS-based geodiversity and threat analysis also helped identify vulnerable geological sites, estimating potential environmental risks and policies that could be taken for long term preservation (Bétard & Peulvast, 2019). Integration of these GIS-based tools enabled stakeholders to incorporate development and conservation in an informed decision-making process with a view to balance development with conservation, thereby promoting responsible geotourism and environmental sustainability (Keskin Citiroglu & Arca, 2023).

3.4.2.3. Conservation planning and stakeholder engagement. Effective conservation planning in geoheritage sites relied on a combination of geotourism and conservation strategies that balanced ecological preservation with sustainable tourism growth (Helmi et al., 2024). Local engagement-based initiatives and inclusive tourism initiatives were key to promoting conservation efforts commensurate with the values and needs of residents while ensuring access for diverse visitor groups (Gravis et al., 2020). For instance, online promotion and marketing strategies exploited the digital tools for announcing awareness creation, appealing to responsible tourists and promoting economic sustainability through heritage-based tourism (Molokáč et al., 2023). Finally, interpretation programs and cultural integration enhanced visitor experiences by providing educational insights into geological heritage, fostering cultural appreciation, and reinforcing the significance of conservation efforts (Migoń & Pijet-Migoń, 2017). Therefore, the combined approaches advocated here ensured that geoheritage management was environmentally responsible and socially inclusive so as to guarantee the long-term sustainability of the conservation initiatives.

3.4.2.4. Geoeducation, science, and digital learning tools. Improvements in digital learning and geoeducation technologies were permitting the spread of geological knowledge in more accessible forms to the general public and the researcher alike, making otherwise complex scientific concepts more accessible to students (Németh, Németh and Procter, 2021). Digital platforms and interactive information used accessible technology to communicate complex science, engaging the public on geoheritage and deepening awareness of geological and environmental science (Lansigu et al., 2014). Additionally, interactive and experiential learning approaches, such as virtual field trips, gamification, and AR, provided immersive educational experiences that bridged the gap between theoretical knowledge and practical understanding (Martínez-Graña et al., 2014). By integrating these tools, geoeducation initiatives could reach a broader audience, promote scientific literacy, and contribute to the long-term sustainability of geoconservation efforts (Long, 2016).

3.4.2.5. Decision-support systems for geoheritage and geopark management. The integration of deep learning models and assessment enhanced data-driven decision-making in geoheritage conservation by enabling accurate predictions of environmental changes and geological risks (Ballesteros et al., 2022). Complementing this, the establishment of legal frameworks and policy development ensured that geoconservation efforts aligned with regulatory standards and sustainable management practices (Coronato & Schwarz, 2022). Additionally, multi criteria decision analysis (MCDA) and risk assessment could assist in strategic planning by evaluating several factors precisely (ecological impact, tourism potential, and conservation needs) to determine the best management of geopark (Keskin Citiroglu & Arca, 2023). These decision support systems worked together to preserve geoheritage sites, maximize economic and educational opportunities, and—most importantly—meet conservation objectives that balanced these values.

3.4.3. Outcomes (O)

The implementation of digital tools and strategic conservation efforts resulted in significant geotourism development and sustainable tourism, fostering economic growth while preserving geological and cultural landmarks (Fassoulas et al., 2022; Ivanović et al., 2023). Additionally, advancements in geoeducation and public awareness enhanced scientific literacy and community involvement, ensuring that local populations and visitors appreciated and contributed to conservation efforts (Chang et al., 2020; Fernández Álvarez, 2019; Quesada-Román et al., 2022). These initiatives supported conservation, environmental sustainability, and ecosystem protection, mitigating the adverse effects of climate change and human activities on geoheritage sites (Leman et al., 2016). In addition, local identities and traditions were promoted through environments for the promotion of cultural heritage and the participation of community engagement integrated with geological features and historical and social narratives

(Cetin et al., 2018; Henriques & dos Reis, 2021). Finally, improvements in policy, governance, and strategic management presented structured manners for geopark administration, so conservation efforts were grouped with sustainable development goals and long-term regional planning (Nakarmi et al., 2023).

3.4.4. Theories (T)

Theories guided research on leveraging digitalization in geoheritage and geoparks. A bibliometric analysis showed that Stakeholder Theory (18 articles), Emerging Theory (15 articles), and Landscape Ecology Theory (15 articles) were the most used, highlighting the role of external pressures and internal capabilities in shaping practices. Technology Acceptance Model (TAM) (14 articles) and Digital Learning Theory (12 articles) were also prominent, corresponding to technological innovation as drivers of sustainable growth and development. Other emerging theories were less explored and these findings highlighted the theoretical frameworks that were central to advancing the field. The complete overview of widely used and emerging theories identified in this study is summarized in Table 8, providing insights into both established and developing theoretical perspectives within geoheritage and geopark digitalization research.

Stakeholder Theory emphasized the importance of engaging various stakeholders, including governments, local communities, tourists, conservation organizations, and businesses, in decision-making processes related to geoheritage management (Gravis et al., 2020). In the context of digitalization and geotourism, this theory highlighted the need for collaborative governance and inclusive strategies to balance environmental conservation with economic and social benefits (Fassoulas et al., 2022). By integrating digital tools such as GIS-based mapping and virtual platforms, stakeholder engagement could be enhanced, ensuring that diverse interests were considered in sustainable geopark and tourism development (Ballesteros et al., 2022).

Emerging Theory referred to the constant development of theoretical frameworks aimed at explaining new phenomena, especially technology, conservation, and geotourism nexus (Ansori et al., 2023). The rise of digital transformation was transforming the management of geoheritage. Emerging Theory on sustainability, smart tourism, and digital innovation provided explanations for how novel technologies (such as AI, IoT, and blockchain) influence conservation work. (Portal, 2023). The evolving perspectives determined what the policymakers and practitioners should do in light of the rapid technological changes and ecological and cultural integrity of geoheritage sites (Nakarmi et al., 2023).

Landscape Ecology Theory focused on the patterns and responses of the landscapes to the process that resulted from the interaction between the natural and human-made system (Melelli et al., 2017). This theory had application in geoheritage conservation from a framework that could clarify the impacts that land use change, urbanization, and climate variability had upon geological formations and biodiversity (Argyriou et al., 2016). UAV technology, GIS, and remote sensing were integrated to provide a more efficient tool for landscape monitoring and geoconservation planning in geologically significant sites with sustainable management (Hoblea et al., 2014).

Technology Acceptance Model (TAM) defined how users really used and adopted new technology according to perceived usefulness and ease of use (Gambino et al., 2019). At the level of geoheritage and geotourism, TAM was of profound importance in order to comprehend how visitors, educators, and conservationists began to incorporate digital tools like AR and VR applications, mobile guides, and web-based GIS platforms (Pica et al., 2018). Ensuring that these technologies were user-friendly and enhanced visitor experiences could accelerate their widespread adoption, ultimately promoting sustainable tourism and digital learning in geoheritage sites (Kim & Lim, 2019).

Digital Learning Theory explored how technology enhanced educational experiences, particularly in interactive and experiential learning (Fernández Álvarez, 2019). Applied to geoeducation, this theory emphasized the role of digital platforms, virtual simulations, and science communication tools in making geological knowledge more accessible (Chang et al., 2020). By integrating AR/VR experiences, online learning modules, and citizen science initiatives, digital learning supported both formal and informal education, fostering greater public awareness and engagement in geoconservation efforts (Martínez-Graña et al., 2017).

3.4.5. Contexts (C)

This study, based on a bibliometric analysis, revealed that Italy (22 articles), Spain (14 articles), and China (10 articles) were the most researched countries in the geoheritage domain, alongside 11 global studies. The prevalence of research from these countries underscored their strong engagement in geopark development, geoheritage conservation, and digital geotourism

Table 8
Widely used and emerging theories.

Theories	Number of articles	References
Stakeholder Theory	18	Ballesteros et al., 2022; Fassoulas et al., 2022; Gravis et al., 2020; Haryono et al., 2022; Morante-Carballo et al., 2022
Emerging Theory	15	Ansori et al., 2023; Nakarmi et al., 2023; Portal, 2023; Quesada-Román et al., 2020; Rodríguez et al., 2022
Landscape Ecology Theory	15	Argyriou et al., 2016; Bétard & Peulvast, 2019; Hoblea et al., 2014; Meini et al., 2018; Melelli et al., 2017
Technology Acceptance Model (TAM)	14	Chin & Wang, 2024; Filocamo, Di Paola, Mastrobuono, & Rosskopf, 2020; Gambino et al., 2019; Kim & Lim, 2019; Pica et al., 2018
Digital Learning Theory	12	Fernández Álvarez, 2019; Chang et al., 2020; Fassoulas et al., 2022; Martínez-Graña et al., 2014; Martínez-Graña et al., 2017

initiatives. The context of geoheritage research spaned multiple domains, including UNESCO Global Geoparks, geotourism strategies, and geological and geomorphological studies, reflecting the multidisciplinary nature of the field (Fassoulas et al., 2022; Frey, 2021; Henriques et al., 2019). Additionally, geoscience education and digital geotourism emerged as critical themes, highlighting the role of technology in promoting awareness and conservation efforts. Specific landscapes such as rivers, lakes, coastal geosites, volcanic and tectonic heritage, national parks, and protected areas were also extensively studied, alongside historical and industrial geosites, karst formations, and mining heritage (Awadh et al., 2022; Bruno et al., 2020; Németh et al., 2021). These diverse research contexts demonstrated the growing intersection between digitalization, conservation, and sustainable tourism in geoheritage management.

3.4.6. Methods (M)

The third component of the ADO-TCM framework, methodology, emphasized the data collection and analysis methods used in research on leveraging digitalization in geoheritage and geoparks. Our analysis revealed a notable preference for quantitative methods, which accounted for 40.60% of studies, followed by qualitative methods (34.10%) and mixed methods (25.30%). Among quantitative methods, GIS-based spatial analysis, remote sensing and satellite image analysis, and multicriteria decision-making (MCDM) were the most commonly employed techniques. On the qualitative side, content analysis, thematic analysis, and case study with document analysis were frequently used to gain deeper insights into the subject matter. These findings demonstrated a clear dominance of quantitative approaches in the field, alongside the growing use of mixed-method strategies to capture the multifaceted nature of geoheritage, geoparks, and sustainable development.

3.5. Future research recommendations

3.5.1. Antecedents

Future research should explore the role of digital tourism and marketing in the post-COVID-19 era, as the shift toward online platforms for tourism promotion continues to accelerate (Fassoulas et al., 2022). The increasing reliance on digital tools for geosites promotion, combined with the rising popularity of social media, presents an opportunity to study how digital engagement influences public interest in cultural and natural heritage (Hoblea et al., 2014). Researchers could investigate how social media data, user-generated content, and aesthetic appreciation contribute to the development of tourism interpretation strategies (Lugeri et al., 2015). Additionally, there is a need to assess the effectiveness of various digital marketing strategies in enhancing public awareness and engagement with geoheritage, particularly in underrepresented or lesser-known geosites (Pica et al., 2018). By integrating data-driven insights, future studies can guide policymakers and tourism stakeholders in designing effective digital promotion strategies for sustainable geotourism.

The accessibility and inclusivity of geoheritage sites remain an underexplored yet critical area of research, particularly in the context of inclusive tourism policies and disability advocacy (Henriques et al., 2019). While there is growing awareness of the need for inclusive tourism, protective legislation and structured accessibility initiatives remain limited (Gravis et al., 2020). Future studies should examine the role of community activism in promoting accessible geological education and public engagement, especially for individuals with disabilities or marginalized groups. Additionally, research can focus on how unique geological formations with cultural significance can be made more accessible to wider audiences, ensuring that vulnerable geosites receive adequate protection and recognition (Fassoulas et al., 2022). Investigating the economic implications of inclusive geotourism—such as its potential for fostering sustainable local economies—can further contribute to the development of comprehensive policy frameworks that balance conservation efforts with equitable access (Leman et al., 2016).

The impact of rapid urbanization and industrial expansion on geoheritage remains an area requiring deeper investigation. As tourism-driven urbanization and economic interests continue to shape landscapes, research should assess the lack of geological awareness among urban planners and policymakers, particularly concerning the protection of indigenous lands and geosites (Németh & Németh, 2023). Furthermore, abandoned mining activities and historical mining landscapes present unique challenges for conservation (Marescotti et al., 2018). Studies should explore how former mining sites, rich in historical and geological significance, can be repurposed for sustainable tourism and education while preserving their heritage (Bruno et al., 2020). Additionally, the role of policy gaps in geoheritage conservation—especially in urbanized regions—deserves attention, as unregulated development threatens the integrity of significant geological formations. Future research should aim to bridge these knowledge gaps by proposing strategies that balance urban growth with long-term geoheritage sustainability (Martínez-Peláez et al., 2023).

3.5.2. Decisions

While significant research has been conducted on GIS-based environmental assessments, digital learning tools, and decision-support systems for geoheritage management, certain critical decision-making aspects remain underexplored (Lansigu et al., 2014). Future research should focus on the development and integration of mobile and web applications for geoheritage, which can enhance accessibility, engagement, and real-time decision-making in geotourism (Németh & Németh, 2023). While VR and AR applications have gained moderate attention, there is still limited exploration of how digital platforms can be used for dynamic interpretation programs and cultural integration (Maloney et al., 2023). Additionally, interactive and experiential learning strategies require further investigation to assess their effectiveness in fostering deeper public engagement and scientific understanding of geoheritage (Fernández Álvarez, 2019). By studying these emerging decision-making tools, future research can provide valuable insights into how digital transformation can bridge the gap between technology, education, and conservation efforts, ultimately supporting sustainable geoheritage management.

3.5.3. Outcomes

While research on geotourism development, geoeducation, and environmental conservation is well established, there is a noticeable gap in studies exploring the role of policy, governance, and strategic management in geoheritage preservation. Future research should examine how regulatory frameworks, governance structures, and institutional policies influence the long-term sustainability of geoheritage sites (Gravis et al., 2020). Additionally, cultural heritage and community engagement remain underexplored areas that warrant deeper investigation (Cetin et al., 2018). Understanding how local communities interact with and contribute to geoheritage conservation—through participatory governance models, traditional knowledge integration, and inclusive decision-making—can provide valuable insights into sustainable site management (Meini et al., 2018). The filling of these gaps will facilitate future research to explore how the economic, environmental, and so-cio-cultural interests can be balanced, and policy and community-driven initiatives can help reinforce their role in the preservation and promoting of geoheritage (Gravis et al., 2020).

3.5.4. Theories

Future research on the geoheritage—empowered by digitalization—can develop additional theoretically grounded frameworks to study geoheritage, offering deeper insights into sustainability, governance, and community engagement. Therefore, Cartographic Theory can be used in the investigation of the role played by computer mapping and GIS technologies in visualizing and interpreting geoheritage sites, improving scientific knowledge and public accessibility (Scarsi et al., 2019). Resource Based View Theory provides a framework to analyze geoheritage assets as strategic resources capable of conferring competitive advantages in geotourism and sustainable site management (Sansò et al., 2015). Additionally, Legitimacy Theory remains underexplored in the context of geoheritage governance, where research could assess how organizations establish credibility through sustainability initiatives and compliance with global conservation standards (Palazzo & Valente, 2024). Cultural Preservation Theory offers a valuable lens to examine how digital tools contribute to safeguarding intangible heritage, ensuring that local traditions and historical narratives remain integral to conservation efforts (Meini et al., 2018). Lastly, applying the Public Engagement Framework can provide insights into how digital platforms foster community involvement, promoting awareness, participation, and long-term stewardship of geoheritage sites (Valentini et al., 2022). By integrating these theories, future research can build a more holistic understanding of how digitalization supports sustainability, policy development, and cultural heritage preservation.

3.5.5. Contexts

Future research on geoheritage digitalization should focus on underexplored contexts such as geoarchaeology and historical geosites, which remain critical yet understudied areas. These sites, which encompass ancient landscapes, fossils, and historically significant geological formations, require innovative digital tools for documentation, interpretation, and conservation (Portal, 2023). Digital reconstruction techniques including 3D modeling and AR might enable public engagement by preserving the scientific and cultural value of historical geosites, using historical geosites to bring them to life (Hoblea et al., 2014). There are also research issues surrounding the use of digital storytelling and technology to publicize geoarchaeology (Lugeri et al., 2015). Examining these ways offers an impetus to striking a balance between promoting conservation and preserving the historical geosites under opportunities of education and economics (Migoń & Pijet-Migoń, 2017).

Similarly, mining heritage and industrial geosites represent another context where digitalization could drive sustainable tourism and heritage conservation (Cetin et al., 2018). These sites, often remnants of historical resource extraction industries, are crucial for understanding industrial evolution, but they face challenges related to environmental degradation and lack of public awareness (Bétard & Peulvast, 2019). Future research should explore effective integration between mining heritage and contemporary geotourism, while examining how virtual and interactive learning tools can enhance visitor engagement at mining heritage sites and foster responsible tourism practices (Marescotti et al., 2018). Additionally, karst and cave geosites are ecologically sensitive and scientifically valuable, which have to be engaged with advanced monitoring and preservation techniques (Hoblea et al., 2014). Real time data on cave conditions that are protected and at the same time used to improve visitor experience could be used through digital mapping, AI driven environmental monitoring as well as mobile applications (Q. Li et al., 2015). By addressing these research gaps, future studies can contribute to sustainable geoheritage management and create innovative strategies for balancing conservation, education, and economic development.

Additionally, geoheritage conservation and tourism participation have great potential for contribution from geo-spatial applications, mobile applications, and e-ticketing platforms (Ansori et al., 2023). Researching the implementation and success of these digital tools in different territorial environments can even better understand how technology can be used to improve visitors' experiences, manage the processes more easily, and promote the geoheritage sites' sustainability (Henriques et al., 2019). Finally, there is a direct need to direct research efforts to certain countries, instead of global or overarching regional ones. More in-depth studies are required to examine the unique challenges and opportunities for digitalization in geoheritage and geoparks in specific countries or regions, such as Southeast Asia or Europe, where digital and sustainability efforts in geoheritage are gaining traction (Melelli et al., 2017).

3.5.6. Methods

Future research on geoheritage digitalization should place greater emphasis on mixed-method approaches, as they remain underutilized despite their potential to provide comprehensive insights (Migoń & Pijet-Migoń, 2017). While quantitative methods dominate the field, qualitative research—currently limited to a few major theories—could be expanded through diverse analytical frameworks to better capture contextual and interpretative dimensions (Bollati et al., 2017). Additionally, underexplored

quantitative techniques such as bibliometric and impact analysis, viewshed and network analysis, and ANCOVA should be further investigated to enhance methodological rigor (Chang et al., 2020). By incorporating these varied approaches, future studies can bridge existing gaps, offering a more holistic understanding of digitalization's impact on geoheritage conservation, geoparks management, education, and sustainable tourism.

4. Conclusion

This review underscores the increasing role of digitalization in geoheritage and geopark management, emphasizing the need for further research to understand how digital tools shape geotourism, conservation, and sustainable development. Our bibliometric analysis and application of the ADO-TCM framework highlight critical gaps in the literature, particularly concerning the antecedents, decision-making processes, outcomes, theoretical foundations, contexts, and methodologies of digital transformation in geoheritage. Future studies should investigate the influence of digital tourism marketing, social media engagement, and inclusive tourism policies in shaping public interest and accessibility to geoheritage sites. Additionally, the underexplored impact of rapid urbanization, industrial expansion, and abandoned mining landscapes on geoheritage preservation requires urgent scholarly attention. Addressing these issues will help bridge policy gaps, enhance conservation strategies, and promote the integration of digital tools into sustainable site management. Further research should also focus on governance, policy frameworks, and community engagement, as these aspects remain relatively understudied in the digitalization of geoheritage. The application of theories such as Cartographic Theory, Legitimacy Theory, and Cultural Preservation Theory can provide deeper insights into the role of digital mapping, governance mechanisms, and heritage safeguarding efforts. Additionally, more diverse methodological approaches—including mixed methods, bibliometric analysis, impact assessments, and advanced geospatial techniques—are needed to generate comprehensive insights into digitalization's effects on geoheritage conservation and geotourism. By addressing these research gaps, future studies can contribute to the sustainable management of geoheritage and geoparks, aligning with global sustainability goals while fostering economic and educational advancements.

CRediT authorship contribution statement

Jessica Hermawan: Validation, Conceptualization, Writing – original draft, Project administration, Visualization, Data curation, Writing – review & editing, Software. **Liliana Inggrit Wijaya:** Writing – review & editing, Formal analysis, Investigation, Funding acquisition, Supervision. **Andri Rianawati:** Software, Writing – original draft, Methodology, Validation, Conceptualization, Writing – review & editing, Resources.

Ethical statement

The authors confirm that no ethical issues are linked to this manuscript or the underlying study. All authors equally contributed to this study. They also confirm that this is an original research work with no plagiarism.

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Declaration of competing interest

The authors declare no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijgeop.2025.05.002.

Data availability statement

The data that support the findings of this study are available from the corresponding author (liliana@staff.ubaya.ac.id) upon reasonable request.

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