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Original paper

Spatial realities: bridging digital heritage, geoinformatics and sustainable development

Hippocrates Manoudakis[1]*, Maria Bakatsaki[2], Stelios Manoudakis[2]

[1]University of Thessaly, Volos, Greece
e-mail: imanoudakis@uth.gr; ORCID: http://orcid.org/0000-0003-4011-2851

[2]Technical University of Crete, Chania, Greece
e-mail: mbakatsaki@tuc.gr; ORCID: http://orcid.org/0000-0001-7614-9002
e-mail: smanoudakis@tuc.gr; ORCID: http://orcid.org/0000-0001-7005-239X

*Corresponding author: Hippocrates Manoudakis, e-mail: imanoudakis@uth.gr

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Abstract: Cultural heritage is a non-renewable and irreplaceable resource, and using digital technologies, especially geoinformatics, has become a powerful means of preserving and promoting it. However, integrating digital heritage, which utilizes geoinformation, into sustainable development discussions remains an ongoing challenge. This paper examines geoinformatics technologies applied to critical domains of digital heritage, including documentation, representation, and dissemination. It also explores digital heritage's threefold role in cultural sustainability: how it mediates society, economy, and environment, develops alongside these pillars, and how geoinformatics becomes embedded within digital heritage. The study employs literature reviews and case studies to investigate the integration of geoinformatics into digital cultural heritage, aiming to inform policy and practice in heritage conservation. As a multidisciplinary field, geoinformatics combines geospatial technologies and information science, such as Participatory Geographic Information Systems (PGIS), to manage, conserve, and promote cultural heritage. Despite these technologies' potential, digital heritage faces challenges like data security, interoperability, cost, and accessibility, alongside issues such as application simplification and speed. Opening access to digital heritage and enhancing ease of understanding are also significant obstacles. Integrating geoinformatics into digital heritage is a milestone in cultural heritage conservation. This interdisciplinary approach strengthens documentation, spatial analysis, and public engagement, fostering greater involvement in protecting shared heritage. As geospatial technologies evolve, collaboration among stakeholders is vital to ensure that cultural heritage preservation aligns with the sustainable development of society, the economy, and the environment.

Keywords: digital heritage, geoinformatics, sustainable development

1. Introduction

Cultural heritage, a repository of human history and identity, is an invaluable asset that must be conserved for future generations. In the digital era, advancements in technology, particularly in the realm of geoinformatics, have revolutionized the way cultural preservation is approached. However, the seamless integration of digital heritage, infused with geoinformation, into the broader discourse of sustainable development remains a complex challenge (Rădulescu et al., 2021).

This literature review explores the multifaceted intersection of geoinformatics, digital cultural heritage, and sustainable development. It is embarking on a comprehensive exploration of the diverse applications of geoinformatics technologies in the fundamental areas of digital heritage, which include documentation, representation, and dissemination (Xiao et al., 2018). Additionally, it scrutinizes the triple role that digital heritage assumes in fostering cultural sustainability, examining its mediation of societal, economic, and environmental pillars of sustainability. Utilizing a methodological framework grounded in literature review and case study analysis, this study seeks to elucidate the integration of geoinformatics and digital cultural heritage within sustainable development. Through an in-depth examination of existing research and practical applications, it is endeavored to inform policy formulation and best practices in heritage conservation. Geoinformatics, as a multidisciplinary field bridging geospatial technologies and information science, emerges as a potent tool for preserving, managing, and promoting cultural heritage (Guo et al., 2020). Furthermore, the journey towards effective integration is fraught with challenges, ranging from data security and interoperability issues to accessibility concerns and the need for application simplification and speed (Paclíková et al., 2018). Combining geoinformatics with digital heritage is a significant leap forward in cultural heritage conservation efforts. This interdisciplinary approach furnishes powerful tools for documentation, spatial analysis, and decision-making and engenders heightened public engagement in safeguarding our shared heritage. The complexities of this integration emerge in the importance of stakeholder collaboration. Concerted efforts are essential in harnessing geospatial technologies and information science to safeguard our cultural legacy while fostering socioeconomic and environmental sustainability. This collective endeavor is indispensable in securing a sustainable future that empowers human equity, diversity, and prosperity for future generations.

2. Methodology

Literature reviews play a vital role in advancing knowledge and shaping effective policies. This research conducted a bibliometric analysis under the framework of a Systematic Literature Review (SLR), an objective academic method for gathering relevant material (Briner and Denyer, 2012). The SLR process is characterized by its transparency and reproducibility, allowing researchers to construct a new conceptual framework and document their field with reliable methods (Snyder, 2019). Specifically, it aims to identify the main factors influencing the integration of geoinformatics with digital heritage in sustainable development (Mendoza et al., 2023). It begins by establishing research criteria and selecting suitable articles through a well-defined search and extraction procedure. The subsequent phase involves a repeated procedure of selecting articles and then analysing and synthesizing them to assess their relevance to the topic. The final phase involves the presentation of the articles categorized by publication year and journal (Sarkis-Onofre et al., 2021).

In a Systematic Literature Review (SLR), the initial step involves establishing search criteria to determine which studies fall within the scope of the investigation (Jaegler et. al., 2018). Therefore, predefined criteria are essential to maintain transparency in the approach. The criteria outlined for this study are as follows:

- SLR methodology adheres to the PRISMA guidelines (Page et al., 2021), utilizing scientific publications sourced from Scopus and WOS databases to investigate the factors hindering and facilitating the integration of Geoinformatics and Digital Heritage practices (Ch'ng et al., 2022) in the framework of Sustainable Development. Many keyword searches are conducted based on various topics, including titles, abstracts, and keywords. The terms used for this search include: ("Digital Heritage," or "Geoinformatics Technologies," "Spatial Data," and "Sustainable Development" or "Sustainable Digital Heritage").
- It has encompassed solely reviewed articles from journals, excluding conference papers, book chapters, review papers and similar sources.
- Articles in the categories of "Art and Humanities," "Business, Management and Accounting," "Computer Science," "Decision Science," "Environmental Science," "Earth and Planetary Science," "Social Sciences" in Scopus and "Environmental Science Ecology," "Computer Science," and "Arts Humanities Other Topics" in WOS are included to ensure that it is predominantly given the focus on the impact of Digital Heritage and Geoinformatics on Sustainable Development field.
- The selected articles are exclusively in English, as most academic journals are published in this language.
- Contemporary articles published from 2020 to 2024 are incorporated into the selection. The selection of articles from 2020 to 2024 in this study is deliberate, aiming to capture the most recent advancements and discussions in the intersection of geoinformatics, digital heritage, and sustainable development. Several key considerations justify this timeframe:
  - Technological Advancements: The rapid evolution of geoinformatics technologies in recent years has significantly enhanced the methods used for cultural heritage conservation. Focusing on publications from 2020 onwards ensures that the latest tools and methodologies are included. For instance, a 2024 study highlights integrating advanced geomatics techniques to monitor and safeguard historical sites efficiently, addressing contemporary challenges posed by climate change (Barrile et al., 2024).
  - Post-Pandemic Research Dynamics: The COVID-19 pandemic has reshaped research priorities, emphasizing the need for digital solutions in cultural heritage preservation. Studies published during this period reflect innovative approaches adopted in response to global restrictions, such as increased reliance on digital platforms and crowdsourcing for heritage documentation. A 2024 study explores

the sustainable development of cultural heritage crowdsourcing projects, offering insights into enhancing their longevity and impact in the post-pandemic era (Zhang and Dong, 2024).

- Alignment with Sustainable Development Goals (SDGs): Recent literature emphasizes the role of digital heritage in achieving the United Nations' SDGs. By concentrating on studies from this period, the research aligns with current global policy frameworks and sustainability agendas. A 2024 article discusses the integration of geoinformatics in cultural heritage conservation, supporting the UN's SDGs through innovative spatial information technologies (Xiao et al., 2018).
- Increasing Interdisciplinary Integration: Sustainable development discussions incorporating geospatial sciences have gained momentum in recent years, as demonstrated by the growing body of research published post-2020 (Guo et al., 2020). The systematic literature review (SLR) methodology identified a clear rise in relevant studies from 2020 onward, reflecting the increasing academic and policy interest in this field.
- Methodological Rigor and Contemporary Policy Relevance: Older studies might not align with the current regulatory frameworks, technological capabilities, and sustainability policies (Labadi et al., 2021). By focusing on the most recent research, this study ensures that its findings are directly applicable to contemporary policymaking and heritage management strategies.
- Systematic Literature Review (SLR) Criteria: The inclusion criteria align with best practices in systematic literature review methodologies (Page et al., 2021), emphasizing selecting the most recent, high-impact publications to maintain academic rigor and reproducibility.

3. Results

Following the methodology based on defined search parameters, 520 articles were retrieved from both databases. Specifically, 183 articles were sourced from Scopus and 337 from Web of Science. After removing duplicate entries, 502 publications were left for further screening, focusing on their titles and abstracts. Articles unrelated to our topic were excluded, resulting in 386 papers for full-text assessment. At this stage, specific articles related to the area of interest and potentially contributing significantly to a particular subtopic were selected. After excluding 242 publications, the final sample comprised 144 articles (Fig. 1).

A structured and thorough presentation of sample data facilitates a more complete examination of the topic under consideration. Figure 2 depicts the distribution of the remaining 144 publications based on their year of publication. The graph shows a notable increase in publications after 2020, signaling a growing interest in sustainable development related to digital heritage and spatial data (Flick, 2018). The emergence of the COVID-19 pandemic has sparked researchers' interest in exploring alternative approaches to improve interdisciplinarity and ensure resilience between the fields of culture, digital technologies, and sustainability (Funada et al., 2023). The COVID-19 pandemic (2020–2022) catalyzed digital heritage and geospatial research, prompting a shift towards remote documentation,

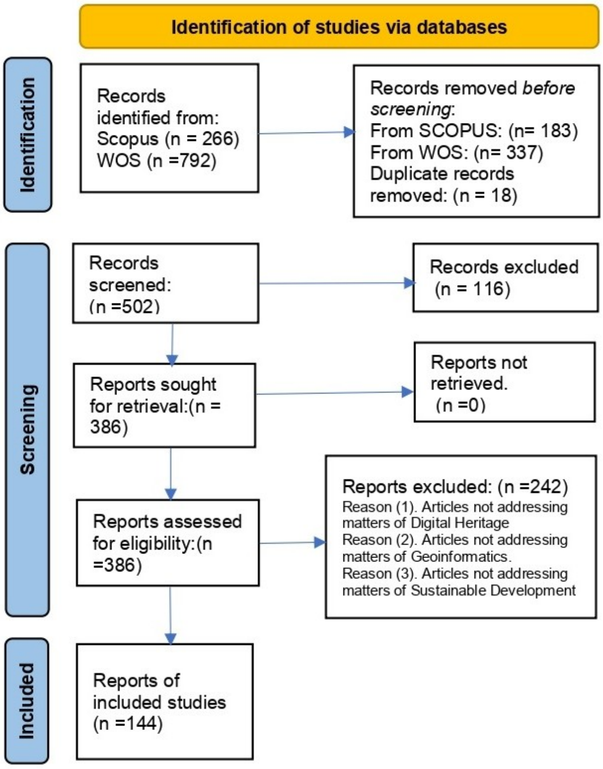

Fig. 1. Systematic literature review process (Page et al., 2021)

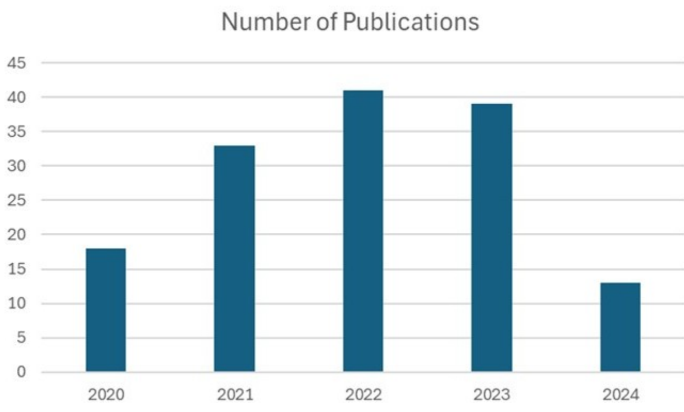

Fig. 2. Year-wise distribution of publications

virtual exhibitions, and digital preservation. This shift is reflected in increased research output focusing on new digital solutions for cultural heritage conservation (Mendoza et al., 2023). The pandemic significantly accelerated the adoption of geospatial technologies and GIS-based approaches, as seen in studies on spatial data visualization, remote monitoring, and accessibility of digital heritage (Clini and Quattrini, 2021; Ahasan et al., 2022). While

2024 has not yet concluded, our study incorporates early-access publications and preprints, ensuring that the most up-to-date research is considered. Additionally, publication trends from previous years (2020–2023) demonstrate a consistent increase in studies related to digital heritage and geoinformatics, supporting the argument that research activity has intensified post-pandemic. Figure 3 illustrates that the journals with the highest number of articles are ISPRS International Journal of GEO Information, with 20 publications; Heritage, with 17 publications; and Big Earth Data, with 12 publications. This is followed by Sustainability (Switzerland) and Heritage Science, which contains 7 articles each. The field ("others") includes 27 journals with 29 issues distributed from 1 to 2 publications per journal.

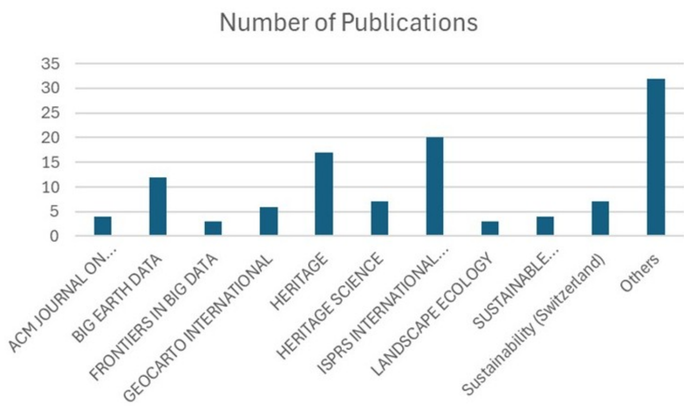

Fig. 3. Journal-wise publication distribution

The SLR methodology identified various factors influencing the contribution of Digital Heritage and Geoinformatics practices to the Sustainability field. It also gauged the prevalence of these factors by assessing their frequency across the selected articles. Krippendorff (2018) suggests that content analysis is a reliable research approach to discern patterns in the contexts where articles are applied. This method should uphold legitimacy, reliability, and reproducibility through a well-defined procedural framework. Initially, the enablers were examined to understand and grasp the factors driving the adoption of Digital Heritage and Geoinformatics practices in Sustainable Development.

From a systematic review of 144 articles, 15 significant enablers were identified, with heritage preservation incentives emerging as the most noteworthy motivator (Fig. 4). Heritage preservation requires a robust digitization framework combined with minimizing environmental impacts and enhancing promotion and preservation (Paschalidou et al., 2022). Also, governmental and non-governmental bodies encourage the adoption of eco-friendly management techniques (Moorthy et al., 2012). Policy frameworks and regulations are needed to guide comprehensive approaches and translate policy decisions into specific, measurable actions (Labadi et al., 2021). Cross-sectoral collaboration encompasses the benefits of cooperation across different sectors (Richards and Bonink, 1995). Understanding whether and how such collaboration can create value for diverse partners is crucial. New knowledge generated through cross-sector collaboration on sustainability enhances academic research and creates business opportunities (Soini and Birkeland, 2014).

Fig. 4. Frequency of Enablers

The remaining enabler parameters are included in the main three mentioned above. Figure 5 presents the 19 barriers that emerged from the review analysis. The three dominant obstacles are Technological Limitations, Financial Constraints, and Policy and Regulatory Barriers.

Fig. 5. Frequency of barriers

4. Co-occurrence analysis

This paper uses co-occurrence analysis to identify patterns and relationships between key terms or concepts in the selected literature body. Specifically, it helps reveal how frequently specific keywords or terms appear in research articles, thereby uncovering thematic clusters and connections between different topics. This analysis is crucial for understanding the research field's structure and identifying the most significant and emerging themes, enabling a clearer picture of how geoinformatics and digital heritage intersect with sustainable development.

To perform the co-occurrence analysis, VosViewer, a tool for constructing and visualizing bibliometric networks allowing three types of visualisation (network visualisation, overlay, and density visualisation), has been used. VosViewer offers multiple ways to display a map, each highlighting different aspects. It includes zooming, scrolling, and searching features, making examining a map in detail easier. These viewing capabilities are particularly beneficial for maps with a moderately large number of items, such as 100 or more (Van Eck and Waltman, 2010).

Network visualisation was used to cluster the manuscript-related data based on the co-occurrence of keywords (Fig. 6). The produced bibliometric graph visualises each keyword as a point on a two-dimensional plane. The results are color-coded depending on

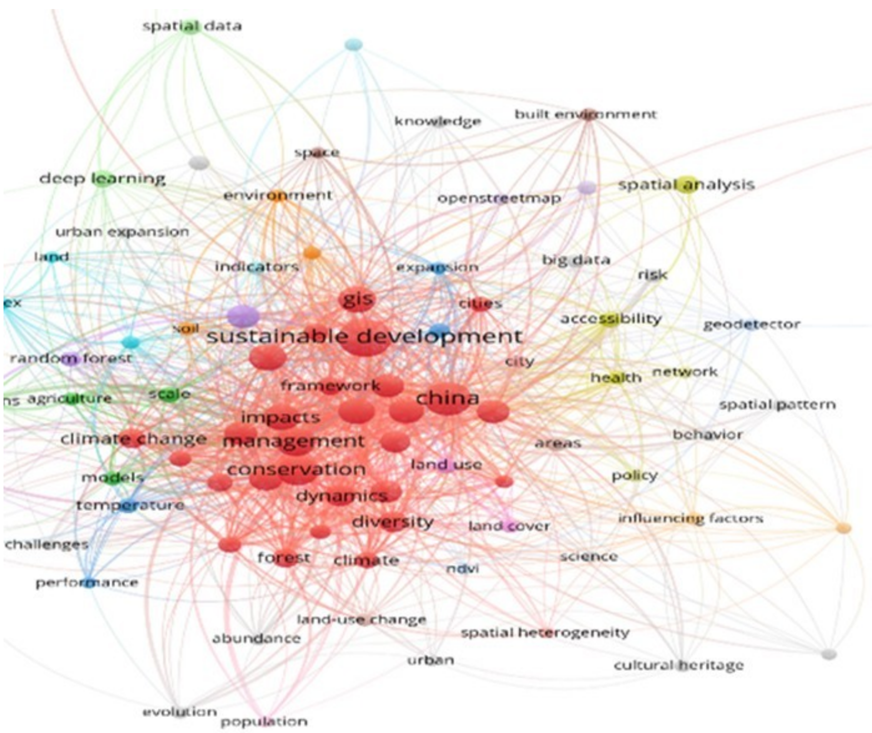

Fig. 6. Keyword co-occurrence map in cultural heritage and geospatial science

each study's similarity, while the node size represents the number of occurrences. The keywords found to co-occur are linked through an arc, the width of which is proportional to the co-occurrence strength, while the node distance indicates the terms' dissimilarity.

A minimum of 8 keyword occurrences was set as a threshold to reduce the map's complexity. This resulted in 85 terms remaining from the 4297 initial ones. The map, depicted in Figure 6, is composed of 1199 links with 1836 total link strength organised in 36 color-coded clusters. Cluster 1, which is the most populated, is represented with red and consists of 26 terms; Cluster 2 is colored green and is made up of 4 terms; Cluster 3 is blue and contains four terms; Cluster 4 to 7 consists of 3 terms, and the least populated clusters Clusters 8 to 17 and Clusters 18 to 36, consist of 2 and 1 term respectively. Below is the distribution of all the terms in the 36 clusters described above. In addition, it presents the ten most common keywords in bold text with the number of occurrences following in the parenthesis.

Table 1. Cluster Distribution (Author's construct)

Cluster	Terms
Cluster 1	biodiversity, China, cities, classification, climate, climate change, conservation, diversity, dynamics, ecology, ecosystem services, forest, framework, gis, impact, land-use, landscape, management, patterns, region, remote sensing, sustainability, sustainable development, urbanization, vegetation
Cluster 2	agriculture, models, scale, systems
Cluster 3	expansion, growth, performance, temperature
Cluster 4	accessibility, health, spatial analysis
Cluster 5	machine learning, monitoring, random forest
Cluster 6	cover, index, land
Cluster 7	area, environment, soil
Cluster 8 to 17	built environment, space, land cover, city, spatial heterogeneity, deep learning, spatial data, geodetector, NDVI, network, policy, OpenStreetMap, urban planning, indicators, sustainable development, geographical weighted, influencing factors, areas, land-use change
Cluster 18 to 36	population, behavior, big data, heterogeneity, coupling coordination degree, abundance, evolution, exploratory spatial data, challenges, knowledge, science, risk, spatial data infrastructure, spatial pattern, cultural heritage, sustainable development, urban, water, urban expansion

From the analysis provided, Cluster 1 through Cluster 36 represents a structured organisation of research articles related to the themes derived from a bibliographic analysis using the SLR PRISMA methodology. These clusters are organised based on the co-occurrence of keywords and their frequency of use in academic publications. Here is what can be deduced for each significant cluster:

Cluster 1:

This cluster is the largest and most populated, focusing primarily on environmental sustainability. It includes critical terms such as biodiversity, climate change, conservation, ecosystems, and land management. These articles often explore how geospatial tools, like GIS and remote sensing, contribute to understanding and managing environmental dynamics, sustainable development, and urbanization impacts.

Cluster 2:

Agriculture, models, and systems characterise cluster 2. This suggests that the articles in this cluster are concerned with geospatial applications in agriculture, possibly focusing on models for sustainable agricultural practices, crop monitoring, land-use patterns, and resource management at various scales.

Cluster 3:

This cluster relates to growth, expansion, performance, and temperature. It focuses on studies that examine the impact of environmental or urban expansion and performance metrics related to temperature dynamics. Topics could include urban heat islands or climate change impact assessments.

Cluster 4:

Here, the focus shifts to accessibility, health, and spatial analysis. Articles in this cluster likely examine how spatial data can be applied to public health, improving accessibility to healthcare facilities and understanding spatial health disparities. Geoinformatics tools like spatial analysis help address health inequalities and improve infrastructure planning.

Cluster 5:

Cluster 5 revolves around machine learning, monitoring, and random forest methodologies. These articles explore advanced computational methods, particularly machine learning, to process and analyze large datasets in geoinformatics. Random forest algorithms suggest focusing on predictive modeling and data classification in environmental monitoring or spatial data interpretation.

Cluster 6:

This cluster includes terms like cover, index, and land, indicating studies on land cover changes and related indexes used to monitor land use. The research likely deals with analyzing satellite imagery or aerial data to understand changes in natural and urban landscapes.

Cluster 7:

With terms like area, environment, and soil, Cluster 7 seems dedicated to soil management and environmental assessments. The articles may explore how geoinformatics aids in mapping soil quality, environmental degradation, and resource management across different areas.

Clusters 8 to 17:

These clusters are more minor and cover more specialized topics, such as:

- Built environment and spatial data (Cluster 8), likely related to urban planning and infrastructure.
- Deep learning (Cluster 9), focusing on integrating AI with geoinformatics.
- OpenStreetMap and urban planning (Cluster 10), which point towards the use of open-source spatial data in planning processes.
- Geographically weighted regression and influencing factors (Cluster 11), used in spatial statistical analysis for modelling complex geographical phenomena.

Clusters 18 to 36:

The minor clusters include niche terms and articles, each having 1 or 2 terms. They likely cover a range of specialized or emerging topics, such as:

- Big data and population behavior (Cluster 18), exploring the relationship between large datasets and human spatial patterns.
- Risk assessment and spatial data infrastructure (Cluster 19), emphasising how geospatial tools support risk management and infrastructure planning.

- Cultural heritage (Cluster 20), focusing on how digital tools preserve cultural heritage within the sustainable development framework.
- Urban water management (Cluster 21), related to geoinformatics applications in managing urban water resources.
- Exploratory spatial data analysis (Cluster 22), focusing on techniques to analyse and visualise spatial patterns in data.

Overall Deduction:

The clusters represent a comprehensive segmentation of articles highlighting the use of geoinformatics and digital tools in addressing various aspects of sustainable development, including environmental management, urban planning, public health, agriculture, and cultural heritage. The most frequently occurring terms – such as sustainability, climate change, GIS, and urbanization – indicate a strong focus on leveraging spatial data to tackle global challenges.

The thematic clusters reflect a rich and diverse application of geoinformatics, with articles ranging from methodological innovations (machine learning, deep learning) to practical implementations in agriculture, conservation, and urban infrastructure. The SLR reveals how interdisciplinary collaboration, advanced technologies, and policy frameworks are central to advancing sustainable development goals using geospatial technologies.

5. Conclusions

The growing interest in the role of culture as the fourth pillar of sustainable development is linked to specific policies and objectives. Their application in climate change, social cohesion, economic development and the promotion and preservation of cultural heritage (Cameron and Kenderdine, 2007) made it necessary to develop all these digital tools to enhance interdisciplinary collaboration and productivity (Astara, 2014). Data collected from a comprehensive literature review aims to understand the important factors for interdisciplinary collaboration. It then explores the challenges researchers, academic institutions and businesses face when implementing a cultural sustainability model (Bahaire and Elliott-White, 1999). This study analysed 144 papers to identify the factors that influence the adoption of enablers and barriers to cultural sustainability practices, and the number of publications expanding alongside the global increase in attention to the field (Sabatini, 2019). A systematic content analysis method was used to improve the reliability and accuracy of the findings. The review revealed a total of 15 enablers and 19 barriers. Among the 15 important enablers, "Heritage Preservation" was mentioned in the most significant publications. This indicates the importance of this enabler in motivating researchers towards more sustainable cultural sustainability practices. The most important barrier to implementing digital innovation techniques in the context of Sustainability was “Technological limitations” (Kanga et al., 2021). While organizations are aware of the benefits of sustainable development practices, transitioning to such practices can be costly and requires technological expertise. So, securing money is crucial for this transformation. Financial institutions should create financing packages designed to assist initiatives in adopting sustainable production technology. The researchers must investigate the successful and productive adoption of new digital technologies by examining the factors that motivate and hinder their implementation. The integration of geoinformatics and digital heritage into sustainable development continues to evolve, offering new methodologies and digital tools for the conservation and promotion of cultural heritage. This study has highlighted the technological advances, challenges, and policy implications that shape this interdisciplinary field. However, the rapid development of digital technologies opens new avenues for further exploration. For example, researchers should explore high-resolution remote sensing, LiDAR (light detection and ranging), and unmanned aerial vehicles (UAVs) to improve heritage documentation and monitoring accuracy. These technologies enable non-invasive surveying techniques, improving the accuracy of spatial analysis in cultural heritage conservation (Xiao et al., 2018; Guo et al., 2020). The field of Artificial Intelligence (AI) and Machine Learning in Digital Heritage is also full of challenges. AI-based algorithms and machine learning models can automate data processing, pattern recognition, and predictive modelling in cultural heritage studies. AI applications could help in damage assessment, historical reconstruction, and 3D modelling of archaeological sites, reducing manual efforts while increasing analytical accuracy (Gregory et al., 2018).

The rapidly evolving immersive technologies (VR, AR, XR) utilised in education and cultural heritage present a promising research direction. Future studies could examine the usability, effectiveness, and accessibility of immersive digital heritage experiences, which allow users to engage with reconstructed historical environments (Zhang et al., 2024). Also, developing standardized frameworks for geoinformatics in digital heritage remains a critical challenge. Future research could explore open-access data-sharing models, cross-platform compatibility, and blockchain integration for secure and transparent heritage management (Vacchio and Bifulco, 2022; Lombardi, 2023). It is suggested that future Systematic literature Reviews broaden the bibliography, which should include monographs that provide in-depth theoretical discussions and historical perspectives on geoinformatics and cultural heritage conservation, conference proceedings as they often include cutting-edge research and emerging methodologies before they appear in journal publications (Lian and Xie, 2024) and case study collections that document practical applications of digital heritage technologies in various geographical contexts. By integrating these sources, future research can enhance interdisciplinary collaboration, capture broader methodological developments, and contribute to a comprehensive understanding of geoinformatics in cultural heritage conservation.

Author contributions

Conceptualization: H.M., M.B.; collection and assembly of data: M.B.; data analysis and interpretation: S.M.; article writing: H.M.; critical revision M.B., S.M. and final approval of the article: M.B.

Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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