Review

Sustainability in Hybrid Technologies for Heritage Preservation: A Scientometric Study

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Abstract: The use of augmented reality applied to museums to preserve and communicate cultural heritage sustainably is a topic of increasing relevance today. Museums play an essential role in preserving and disseminating culture and history, and augmented reality has emerged as a powerful technological tool to enrich the visitor experience and ensure the sustainable preservation of cultural heritage. The fundamental objective of this literature review is to explore and understand the key contributions that are being made in the field of augmented reality applied to museums, with a focus on sustainability. The literature related to this topic is dispersed in various sources of information, which motivates the need to carry out a detailed and systematic analysis incorporating sustainability aspects. To carry out this analysis, the metaphor of the "tree of science" is used. This metaphor provides a structured approach that is applied in two complementary ways. Firstly, it focuses on collecting and analyzing scientometric statistics that cover data on countries, authors, academic institutions, and research centers involved in developing augmented reality applications for museums with sustainable methodologies. This quantitative perspective offers a global view of the contributions and their geographical scope including their sustainability impact. Secondly, an evolutionary analysis based on the "tree of science" is carried out. This historical approach examines the origin and evolution of contributions in the field of augmented reality applied to museums, from its first manifestations to the most recent innovations, with an emphasis on sustainable practices. This historical approach is essential to understanding the trajectory and development of augmented reality applications in the museum context and their role in promoting sustainable cultural heritage preservation. This review aims to provide a complete and contextualized view of the use of augmented reality in museums for the sustainable preservation and communication of cultural heritage. Through a multidimensional approach encompassing scientometric statistics and historical analysis, we seek to shed light on this technology's most significant contributions and evolution in the museum sector, with a particular focus on sustainability.

Keywords: on-site museum; ex situ museum with sustainable practices; put in value; tangible items; intangible elements with eco-friendly emphasis; geosites; cultural heritage through the lens of sustainability; augmented reality

1. Introduction

The tourism industry, a fundamental pillar of the global economy, has provided employment and sustenance to many. However, this sector has faced unprecedented challenges due to the COVID-19 pandemic, which has generated the need for innovative and sustainable solutions to aid in its recovery during and after the crisis [1]. In this search, information technology has emerged as a crucial component [2]. From interactive web platforms to georeferenced applications, the evolution of technology in tourism has been remarkable [3]. Yet, these advancements have often struggled to provide authentic sustainable and value-added experiences to tourists. Addressing these gaps, augmented reality (AR) has emerged as a disruptive technology, transforming the way users interact with tourist destinations, especially in museums, and the sustainable preservation of cultural heritage.

This article extends its analysis beyond the realm of tourism, recognizing that cultural and natural heritage faces its own unique challenges and opportunities in the digital era, particularly in adopting sustainable practices. Based on an extensive review of the literature and various research reports, we address how emerging technologies are reconfiguring the practices of conservation, management, and communication of heritage, with a focus on sustainability. This review highlights the growing application of hybrid immersive technologies in museums and GeoCities, focusing on their ability to support the sustainable preservation and communication of heritage. We acknowledge the profound transformation that digitalization and immersive technologies are making to the heritage sector, while emphasizing sustainability. Therefore, we integrate case studies, theoretical analysis, and empirical evidence that illustrate how these tools not only improve the accessibility and interpretation of heritage but also raise critical questions about authenticity, sustainability, and inclusion. This multidimensional approach allows for a richer understanding of the complexities associated with digital change in heritage, highlighting both the positive advances and the ethical and practical challenges that arise, particularly those related to sustainable practices.

This literature review delves into various studies on the application of AR in museums and heritage conservation, with a focus on sustainability. A growing body of research has begun to explore this field, indicating a shift towards innovative approaches in heritage communication that are environmentally conscious [4]. Although virtual reality has been a focal point, its accessibility challenges due to technical and hardware requirements are notable [5]. Some studies have also integrated artificial intelligence to enhance the museum experience [6]. However, comprehensive research on how AR can sustainably revolutionize interactions with cultural heritage is still in its infancy. Focusing on how AR applications can support preservation procedures, in addition to communication and enhancement actions, this article aims to bridge this gap with an emphasis on sustainable methodologies. It investigates how AR not only enhances the visitor experience but also plays a crucial role in heritage preservation by enabling interactive and engaging methods to document, display, and interpret historical artifacts and sites in a manner that aligns with sustainable principles. Additionally, the concept of "GeoCities" is defined and explored within this context, particularly how they can contribute to sustainable urban development. "GeoCities" refers to urban areas or cities where geolocation technologies, including AR, are extensively applied to enhance urban experiences, tourism, and heritage conservation. This concept entails the integration of AR into urban landscapes, allowing tourists and locals to interact immersively and informatively with cultural and historical contexts, in an environmentally responsible manner.

In conducting this analysis of the inclusion of hybrid immersive technologies in museums and GeoCities for the preservation and communication of heritage, diverse and significant implications are identified across various academic disciplines, with a perspective on sustainability. In the humanities, these technologies can revolutionize interaction with history, art, and culture by providing more interactive and attractive methods for narration and interpretation, while also considering their environmental

impact and promoting sustainable cultural engagement. From an economic perspective, they can significantly influence tourism, creating new attractions and enhancing visitors' experiences, which could lead to increased revenue for cultural sites and surrounding areas, as well as fostering growth in technological sectors, with an eye on sustainable economic development.

In urban studies and geography, these technologies enable urban planning, historical reconstruction, and cultural preservation, helping to visualize changes and understand urban evolution in a sustainable framework. In sociology and anthropology, they impact how individuals and communities interact with their heritage, democratizing access to cultural experiences but also raising questions about authenticity and cultural representation within sustainable cultural ecosystems. In terms of pedagogy, they transform learning by offering opportunities for experiential and situated learning, making locations and experiences that would be otherwise inaccessible available for study and exploration in an ecologically sensitive manner. In the STEM disciplines, these technologies have specific implications: in science, for simulations and visualizations that are ecologically aware; in technology and engineering, as fundamental fields in the creation and improvement of these technologies with a sustainable approach; and in mathematics, in the development of algorithms that drive immersive experiences while considering environmental sustainability. The integration of hybrid immersive technologies represents a multidisciplinary opportunity with far-reaching implications for sustainable cultural heritage management. They promise increased engagement, democratized access, and innovative educational tools but also present challenges related to authenticity, ethical considerations, and the digital divide within the context of sustainable development. Each discipline can contribute to a holistic understanding and responsible deployment of these technologies, ensuring they serve to enrich and preserve cultural heritage in an inclusive and meaningful way while adhering to sustainability principles.

Employing search equations in academic databases such as WoS and Scopus, this article gathers and analyzes relevant information, with an emphasis on sustainable practices in cultural heritage management. The collected data, after deduplication, is examined through the metaphor of the "tree of science" (ToS), using the Tosr R tool (https://cran.r-project.org/web/packages/tosr/index.html, accessed on 20 September 2023). This scientometric analysis aims to understand the global relevance of this topic and its multiple components, particularly focusing on the sustainable aspects of technological applications in heritage preservation. The review is developed in three parts: The first part describes the methods and key aspects of the "tree of science" used in the research with a sustainable lens. The second part presents an in-depth analysis of the findings, highlighting countries with significant contributions, key authors, and knowledge networks in the context of sustainable development in the heritage sector. The third part, drawing on the metaphor of the "tree of science", traces the thematic evolution using "root" for foundational elements, "trunk" for thematic development, and "leaves" for emerging trends and directions in the field of AR and its application in museums and GeoCities for heritage preservation and communication while prioritizing sustainability and environmental responsibility.

2. Methods

In the current digital era, the preservation and communication of cultural heritage face new challenges and opportunities, with a focus on sustainability. With the advent of advanced technologies like augmented reality (AR), 'on-site' and 'ex situ' museums, as well as Geosites, have a unique opportunity to transform the way they present and contextualize both the tangible and intangible elements of cultural heritage in a sustainable manner. AR is not just a tool to visually enhance the display of artifacts and historical narratives, but also a means to emotionally connect visitors with the cultural legacy more deeply and interactively while promoting sustainable practices. In this context, a crucial research question arises: "How can augmented reality transform the presentation and perception of

tangible and intangible elements in 'on-site' and 'ex situ' museums, as well as in Geosites, to enhance and valorize cultural heritage sustainably?" This question seeks not only to explore the potential of AR to enrich the user experience and improve the understanding of cultural heritage in different environments but also to identify and analyze strategies and practices that allow museums and cultural sites to effectively employ this technology to preserve and communicate the richness of cultural heritage to a broader and more diverse audience in an environmentally and culturally sustainable way.

To carry out the analysis focused on the use of disruptive technologies such as augmented reality in the context of cultural heritage preservation in museums through a sustainability lens, we adopted a bibliometric review approach [7]. This approach allowed us to identify and highlight the most significant contributions related to the integration of augmented reality in the museum environment, especially in the new dynamics emerging in the post-pandemic period and their alignment with sustainable practices. We chose to utilize the academic databases WoS and Scopus, renowned for housing a vast collection of peer-reviewed academic documents. Despite the recognition of IEEE and ACM as prominent research databases in computing, we opted to confine our search exclusively to Scopus and WoS. This decision was informed by the extensive time investment required for preprocessing. Additionally, both IEEE and ACM are indexed in Scopus, further justifying our choice to focus on these two databases to ensure a comprehensive understanding of sustainable applications in cultural heritage. For future scientometric research, particularly in the realms of computing and engineering with a sustainable focus, we advocate the inclusion of sources such as IEEE and ACM. These databases are notable for their comprehensive coverage and depth in these specific fields, offering valuable insights and data for more nuanced analysis, including sustainable approaches in heritage technology. The merging of results from both databases, though complex, was executed using specialized tools such as Bibliometrix [8] and the Tosr processing package. This merging process enabled us to obtain a more consensus-based and comprehensive set of results regarding scientific publications related to augmented reality and its influence on the tourism sector, particularly during a period when this sector was heavily impacted by the COVID-19 pandemic and the pressing need for sustainable solutions.

Table 1 details the key variables considered during this literature review. The keywords used included "on-site museum", "ex situ museum", "put in value", "tangible items", "intangible elements", "geosites", "cultural heritage", and "augmented reality", as the main search concepts, with a special emphasis on their sustainable integration. The analysis period spanned from 2000 to the present date, resulting in the identification of 1.123 documents in Scopus and 317 in WoS. Subsequently, after the data fusion process, we obtained a consolidated set of 1189 records, eliminating duplicated documents found in both databases. These 1189 articles were distributed across various categories: conference papers (605, or 50.63%), articles (409, or 34.23%), book chapters (71, 5.94%), conference reviews (53, or 4.44%), reviews (37, or 3.1%), early access (5, or 0.42%), books (3, 0.25%), errata (3, 0.25%), editorials (2, or 0.17%), proceedings papers (1, or 0.08%), book reviews (1, 0.08%), corrections (1, 0.08%), editorial material (1, or 0.08%), letter (1, or 0.08%), notes (1, or 0.08%), and retracted (1, or 0.08%). This percentage analysis reflects that most publications are from conference papers and articles, underscoring the relevance and breadth of research on the application of augmented reality in the tourism sector and the preservation of cultural heritage in museums with an increasing focus on sustainable methodologies and practices.

Augmented reality (AR) offers a significant contribution to the sustainable preservation and enhancement of cultural and natural heritage, interacting with key concepts such as "on-site museum", "ex situ museum", "put in value", "tangible items", "intangible elements", "geosites", and "cultural heritage". In on-site museums, where objects or sites of interest are displayed in their original location, AR provides enriched contexts, enabling virtual reconstructions and interactive narratives that enhance the visitor experience in an environmentally sustainable way. On the other hand, in ex situ museums, where

items are displayed outside of their original context, AR can virtually recreate the original setting, helping visitors better understand the significance and environment of the objects while minimizing ecological impact. The phrase "put in value" refers to the process of highlighting the importance of both tangible and intangible heritage elements in a sustainable manner. Here, AR is particularly valuable as it can bring to life intangible aspects such as stories, traditions, and sounds, as well as provide detailed insight into tangible objects with minimal environmental disruption. For instance, in the case of "geosites", sites of geological significance, AR can reveal historical geological processes and features that are not immediately visible, thus enhancing educational and preservation efforts sustainably.

Table 1. Search results for parameters in the databases.

Parameters	WoS	Scopus
Range	2000–2023	
Date	20 September 2023	
Document Type	Article, book, book chapter, conference proceedings	
Words	"on-site museum", "ex situ museum", "put in value", "tangible items", "intangible elements", "geosites", "cultural heritage", and "Augmented reality"	
Results	317	1123
Total (WoS + Scopus)	1123	

To carry out the detailed scientometric analysis in this article, two distinct phases were conducted, focusing on the use of augmented reality in museums for the sustainable preservation and communication of cultural heritage. In the first phase, a general overview of the various applications of augmented reality developed in the context of museums and their contribution to the sustainable preservation and communication of cultural heritage was provided. During this stage, the production of documents was analyzed by country, journal, and relevant authors in this field of study. This comprehensive review offers a complete view of the state of production worldwide concerning the application of augmented reality in museums to sustainably preserve and communicate cultural heritage.

The second phase was oriented towards a deeper analysis of the different contributions to this area of knowledge, using the metaphor of the 'tree of science' (ToS). Figure 1 presents a detailed representation of the PRISMA scheme, specifying all the stages that were carried out to consolidate the information. To perform the analysis of the collected information, a code developed in R Studio by Core of Science (https://github.com/coreofscience, consulted on 20 September 2023) was utilized. The preprocessing was divided into two parts. The first part involved text mining of Scopus references, as they contain all the important information but in various formats. From this text-mining process, data on authors, years, journals, and titles were extracted. The second part involved web scraping using the DOI found in the WoS references. For this capture, it was necessary to consult the CrossRef app using the DOI to retrieve data on authors, years, titles, and journals. Through this process, the two databases were consolidated, and the result was an Excel file with 22 sheets containing all the detailed information from the combined queries, which is essential for generating scientometric analyses, with a focus on sustainable practices in AR applications.

To generate the ToS, a citation network was constructed from the articles identified in the search and their corresponding references. The SAP algorithm was then employed to categorize the articles into root, trunk, and leaves within this network with an emphasis on highlighting contributions that focused on sustainability in the context of augmented reality in museums. This algorithm mimics the movement of raw and processed sap within a plant, assigning values to root articles and progressing through the tree to the leaves, and then retracing to reassess SAP values, thereby mapping the evolution and impact of sustainable practices in this field. A comprehensive explanation of this methodology is detailed in the work of Valencia-Hernandez et al. [9]. Additionally, the branches of the ToS

were delineated using the clustering algorithm developed by Ghosh et al. [10], focusing on the two largest clusters of article nodes and identifying the prevalence and integration of sustainability-oriented research within these clusters.
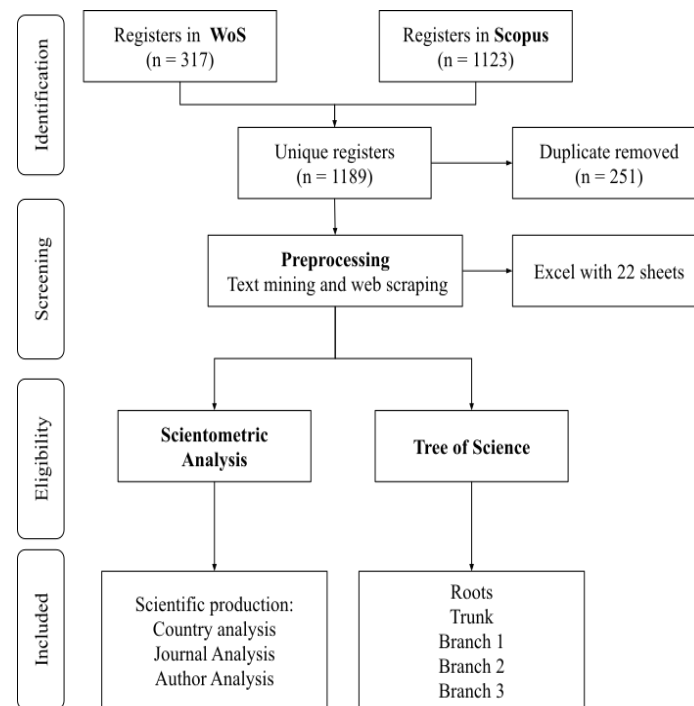

Figure 1. PRISMA diagram for preprocessing data.

This code allowed for the extraction of relevant information regarding the results obtained through the search chain, focusing on the specific contributions related to the application of augmented reality in museums to preserve and communicate cultural heritage sustainably. In this way, a structured and comprehensive investigation was conducted, spanning from a general overview of production to a detailed analysis of specific contributions in the field of augmented reality applied to museums. This provides a comprehensive understanding of the role of this technology in the preservation and dissemination of valuable cultural heritage in museums worldwide with a particular focus on how these technologies can be applied sustainably and responsibly.

2.1. Scientometric Analysis: Unraveling the Contribution of Augmented Reality in Museums and Cultural Heritage with Emphasis on Sustainability

To quantitatively delve into the analysis of scientific data, we employ scientometrics, a discipline that allows us to unravel crucial factors in this context. Scientometrics empowers us to identify significant elements, such as author interactions, interwoven citation networks, and the ever-evolving annual production, with a special focus on sustainable practices in these areas. Among the prominent methodologies for conducting this analysis, we find citation-based analysis [11], collaboration network-based analysis [12], and analyses rooted in intellectual structure [13], all of which are now being re-evaluated under the lens of sustainability.

In our endeavor to comprehend the valuable contributions augmented reality brings to the realm of museums and sustainable cultural heritage preservation, our first step was to unveil which countries lead in terms of publications and, consequently, the application of this technology with sustainable implications. Additionally, we delved into the annual evolution of related scientific publications and explored journals that traditionally excel in disseminating advancements in this field while promoting sustainable methods. These assessments were based on the thorough evaluation of consolidated databases such as

Scopus and WoS. To achieve a deeper and more comprehensive analysis, we employed the technique of explanatory clusters.

This scientometric analysis provided us with a holistic view of the relevance of augmented reality in the context of museums and cultural heritage preservation, with a particular emphasis on sustainability. By identifying leading geographical areas in research, collaboration patterns among researchers, and publication trends over time, we can appreciate the increasing significance of augmented reality as a transformative tool in the preservation and communication of cultural heritage worldwide in a manner that is both effective and sustainable.

2.2. The Evolution of Knowledge: The Metaphorical "Tree of Science"

The concept of the "tree of science", commonly known as ToS (tree of science), is based on a metaphorical interpretation that evokes the image of a tree [14]. In this metaphor, articles located at the root represent the theoretical and foundational basis of a developing field of research. As we ascend towards the tree's trunk, we identify how these research endeavors strengthen and evolve, in the process making significant contributions to the development of the discipline. Finally, the tree's leaves reveal current trends in application, in this case, where technologies are heading to support and enrich the tourism sector with an added focus on sustainable practices and eco-friendly innovations.

This methodological approach, the "tree of science", has been widely employed in various fields of knowledge, spanning from economics [15] to education [16], through marketing [17] and many other disciplines. Its applicability lies in its ability to provide a visual and conceptual representation of the evolution of knowledge in a specific area. In our specific context, it allows us to trace the developmental trajectory of augmented reality about museums and cultural heritage preservation, from its theoretical roots to the branches pointing toward new directions of technological application in the tourism domain with an emphasis on sustainable development and eco-conscious methodologies.

The SAP algorithm is a comprehensive multi-step process designed to analyze and structure a subset of academic papers into a directed graph, known as the "tree of science". It begins by generating a directed graph G from a subset of documents V obtained from WoS and Scopus, where each directed edge represents a citation from one paper to another. This graph is then refined through a series of filtering steps, including selecting the largest connected component, removing loops, eliminating duplicate edges, and discarding vertices with specific criteria for the in-degree and out-degree to form a new graph G'. The algorithm then proceeds to classify the vertices into roots, leaves, and trunks based on their citation relationships and other criteria such as out-degree and in-degree. For example, roots are identified as vertices with an out-degree of zero, and their significance (SAP) is determined by their in-degree. Leaves are vertices with an in-degree of zero, and their importance is assessed based on the number of paths from these leaves to the roots. The trunk classification involves a more complex process, identifying key vertices that act as the main conduits between the roots and leaves of the graph.

Throughout these steps, various functions from the Igraph library are utilized to efficiently select, simplify, and analyze the components of the graph. This includes functions like Graph.clusters(), Graph.simplify(), and Graph.vs.select(), which help in manipulating and refining the graph based on specific parameters. The algorithm constructs the tree of science by creating a subgraph that includes the roots, leaves, and trunk vertices along with their associated edges. This tree represents a structured and hierarchical representation of the academic papers, illustrating the foundational works (roots), emerging topics (leaves), and the pivotal research (trunk) that connects and contextualizes the field.

3. Results

3.1. Scientometric Insights

Figure 2 illustrates the articles produced over the past 22 years, specifically focusing on the application of augmented reality in the tourism sector, with a significant emphasis

on museums and cultural heritage and increasingly incorporating sustainable practices and considerations. As depicted in the graph, production has steadily increased. It is worth noting that the initial works, published in 2001, have received the highest number of citations, as they were pioneering contributions in this field, particularly in the context of museums and cultural heritage with early mentions of sustainability. Starting in 2010, the increasing publication trend became evident in both the WoS and Scopus databases, indicating the growing relevance of augmented reality in the preservation and exhibition of cultural heritage within museum environments, with a clear tilt towards sustainable methodologies. The selection of the works for the diferents periods are based on their distinctive and pioneering contribution to the advancement of hybrid immersive technologies in museum and GeoCities contexts with a focus on eco-friendly and sustainable solutions. Each of these studies represents a significant leap in the application and understanding of augmented reality, virtual reality, and mixed reality in cultural and educational realms while addressing sustainability concerns. From technological innovations that enable new ways to explore outdoor archaeological sites in an eco-conscious manner to the development of intuitive interfaces that enhance user interaction and experience with sustainability in mind, these works have marked important milestones in the evolution of the field. They have been selected for their innovative approach to improving user interactivity and participation, as well as their ability to transform education and cultural understanding through immersive experiences while considering environmental impact and sustainability. Additionally, they address critical aspects such as content management, accessibility, and inclusion, demonstrating the potential of these technologies to provide richer and more contextual cultural experiences, and underscoring their relevance in the preservation and communication of heritage in a sustainable context. Furthermore, they have been globally accepted due to the broad number of citations they have received, reflecting their impact in promoting sustainable cultural experiences.
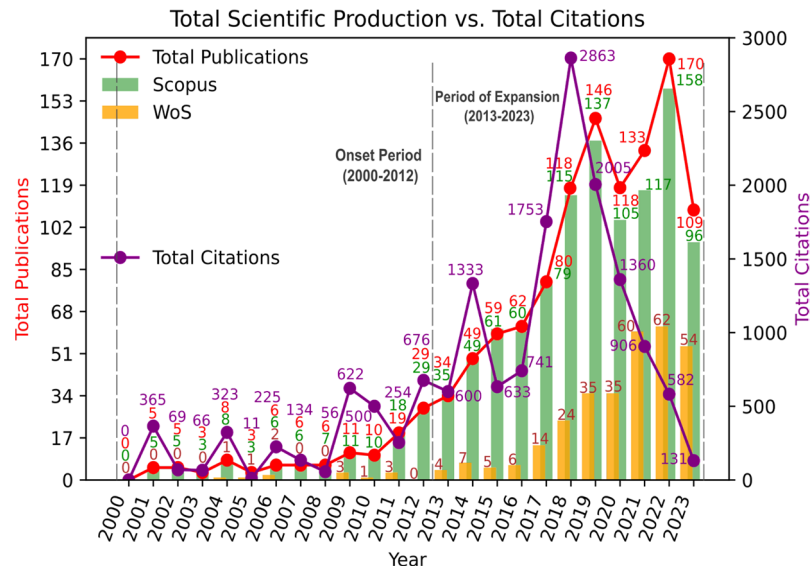

Figure 2. Total production vs. total citations.

Initial foundational phase (2000–2012): To adequately understand this initial phase, it is essential to highlight the close relationship between the evolution of publications and the advancement of augmented reality technology and its associated devices with an emerging focus on sustainability. During this specific period, a total of 111 publications were produced, with 3301 citations, of which 110 are registered in the Scopus database, while 11 are present in the WoS database. This phase laid the foundations for a field of study that would prove to be of great importance, especially in the context of its application in museums and cultural experiences with a growing consciousness towards sustainable practices. Augmented reality (AR) began its journey towards digital transformation in 1999

with the creation of ARToolkit version 1.0, pioneering software that opened the doors to a new dimension of interaction between the digital and physical worlds while considering the implications for sustainable development. This significant milestone marked the beginning of an era in which technology began to overlay virtual information on the real environment, allowing users not only to observe but also to interact with a digitally enriched space in a more eco-friendly manner. Since then, AR has evolved extraordinarily, being integrated into various sectors such as entertainment, education, and industry, redefining the way we interact with our environment, and expanding the boundaries of our perception, while increasingly incorporating sustainability into its applications; see Table 2.

Table 2. Initial foundational phase (2000–2012).

Ref.	Year	Author	Key Contribution Summary
[18]	2001	Gleue	Gleue's work is notable for integrating mobile augmented reality in outdoor settings, specifically within the Archeoguide project, with a focus on sustainable tourism. His development of mobile devices tailored for AR applications provided groundbreaking ways for visitors to interact with historical and archaeological sites through enriched, educational, and interactive experiences, emphasizing eco-friendly practices.
[19]	2001	Kato	Kato's research on tangible augmented reality (TAR) represents a significant stride in creating intuitive interfaces for human–computer interaction, incorporating sustainable design principles. By merging physical objects with digital augmentations, his work has opened new, interactive avenues for museum visitors and GeoCities explorers, fostering a participatory and immersive understanding of cultural heritage, with an eye on sustainability.
[20]	2002	Dahne	Dähne's contribution to the architectural development of the Archeoguide system integrates sustainable outdoor mobile augmented reality platforms. His work has been instrumental in advancing the use of technology to deepen the interaction and interpretation of cultural heritage through detailed, contextual AR presentations that respect and preserve the natural environment.
[21]	2002	Mogilev	Mogilev introduced the AR Pad, an innovative interface designed for collaborative, face-to-face interactions using augmented reality, with applications enhancing sustainable tourism practices in museums and GeoCities. This interface is particularly significant for museums and GeoCities, where it offers novel ways for visitors to engage with exhibits and heritage sites, promoting dynamic, real-time information sharing and enhancing the collective exploration of culture in an eco-friendly manner.
[22]	2003	Ikeuchi	Ikeuchi's "Great Buddha Project" is a pioneering effort in the digital preservation of cultural heritage using virtual reality, with a strong emphasis on sustainable methods. This project demonstrated the potential of detailed observations and VR systems to accurately model historical monuments and artifacts, offering invaluable tools for study, preservation, and the virtual exploration of cultural heritage while minimizing environmental impact.
[23]	2003	Dunston	Dunston's study highlights the advantages of mixed reality (MR) in perceiving designs and interacting with cultural heritage, integrating sustainable approaches in their application. By blending elements of VR and AR, his work provides insights into how MR can create immersive environments where physical and digital objects coexist, thereby revolutionizing visitor perception and understanding in museums and historical sites with sustainability in mind.
[3]	2004	Wojciechowski	Wojciechowski discusses the use of virtual and augmented reality to create immersive museum experiences, focusing on sustainable practices in 3D visualization and user interaction. The article delves into methodologies for 3D visualization, user interaction, and information presentation, offering case studies and practical examples that showcase how digital exhibitions can be enhanced through these emerging technologies while maintaining ecological balance.
[24]	2004	Woods	Woods explores how augmented reality can enrich exhibitions and presentations in science centers and museums, with a special focus on sustainable educational practices. His work focuses on making visitor interactions more engaging and educational, highlighting the transformative potential of AR in providing a deeper, more contextual experience of cultural and scientific heritage in an environmentally conscious way.
[25]	2005	Demiris	Demiris introduces intGuide, a platform for implementing personalized and contextual augmented reality experiences in cultural settings, emphasizing sustainable information delivery. This technology stands out for its ability to provide enriched information and visualizations tailored to the user's specific context, significantly enhancing the learning and discovery experience in museums and historical sites with minimal environmental impact.

Table 2. *Cont.*

Ref.	Year	Author	Key Contribution Summary
[26]	2005	Billinghurst	Billinghurst's work focuses on the key principles and practices for designing effective augmented reality interfaces, incorporating sustainability considerations. His research is especially relevant to museums and cultural heritage, as it highlights how well-designed AR interfaces can transform visitor experiences by enabling interactive digital overlays on actual artifacts and historical reconstructions in a sustainable and environmentally friendly manner.
[27]	2006	Jacobs	Jacobs addresses the classification and implementation of lighting techniques in mixed reality environments with a focus on energy efficiency and sustainability. His research is pivotal for museums and urban settings, where advanced lighting in MR can significantly enhance how visitors perceive and understand exhibitions and historical spaces while being mindful of energy consumption and environmental impact.
[28]	2006	Haller	Haller offers a comprehensive overview of emerging technologies in augmented reality, emphasizing sustainable interface and design aspects for enriching cultural experiences. His work highlights how AR can transform visitor interactions with heritage, providing deeper and more immersive explorations of culture and history with an emphasis on ecological responsibility.
[29]	2007	Schmalstieg	Schmalstieg examines the use of handheld augmented reality devices, considering their environmental impact and promoting sustainable user experiences in museums and historical sites. By providing an accessible and personal interface, his study shows how these devices can transform visitor interactions, offering contextualized information and immersive visualizations for a more in-depth cultural exploration while being eco-conscious.
[30]	2007	Hwang	Hwang's research on markerless augmented reality tracking in mobile devices, within the context of digital art, demonstrates advancements in user interaction with cultural heritage, focusing on low environmental impact technologies. This technology allows for more intuitive and marker-free interactions, enriching the museum and urban cultural experience with flexible, immersive content that adheres to sustainable practices.
[31]	2008	Cutrí	Cutrí focuses on the enhancement of cultural heritage experiences through mobile technologies in urban settings, with an emphasis on sustainable tourism development. The case study of Locri exemplifies how mobile devices can transform the exploration and interaction with a city's historical heritage, providing immersive and personalized access to historical information and narratives in an environmentally sustainable way.
[32]	2008	Gilroy	Gilroy's "E-tree" is an augmented reality art installation exploring the intersection between AR technology and emotional artistic expression, with a focus on sustainable artistic practices. This project demonstrates how AR can create deeply personal and interactive art experiences, offering new perspectives on the interpretation and appreciation of heritage and art in both museums and urban spaces while being mindful of sustainability in the art world.
[4]	2009	Styliani	Styliani provides a detailed analysis of virtual museums, including their technical, cultural, and educational implications, with a strong focus on sustainable virtual museum experiences. The study highlights the unique opportunities virtual museums offer for presenting and exploring urban cultural heritage, providing immersive experiences that allow for a deeper understanding of a city's historical and cultural narrative in a sustainable digital environment.
[33,34]	2009	Choudary	Choudary introduces MARCH, a mobile augmented reality platform designed for cultural heritage, emphasizing sustainable and eco-friendly approaches in visitor experiences. This platform is significant for its ability to offer new dimensions to visitor experiences in museums and urban cultural spaces, allowing for interactive and contextual exploration of heritage through AR-enriched content while highlighting sustainable interactions and engagement in cultural contexts.
[5]	2010	Anderson	Anderson reviews the current state of serious games developed for cultural heritage, analyzing their potential to engage and educate users interactively with a focus on sustainable gaming practices. The review emphasizes the opportunity these games provide for enriching cultural experiences in urban environments and museums, offering innovative and immersive ways to learn about history and heritage while promoting sustainability in gaming content.
[35]	2010	Lu	Lu addresses technical challenges in outdoor augmented reality, focusing on strategies for effectively overlaying digital information in heritage sites with minimal environmental impact. His work is crucial for enhancing the accuracy and immersion of AR experiences in cultural and historical contexts, offering technical solutions that significantly contribute to the preservation and communication of heritage in an environmentally responsible manner.
[36]	2011	Haydar	Haydar explores the use of virtual and augmented reality for the virtual exploration of underwater archaeological sites, with a focus on sustainable exploration methods. This research provides valuable techniques for creating immersive experiences, enabling virtual access to otherwise inaccessible heritage sites, and offering new dimensions for the exploration and communication of underwater cultural heritage in a way that preserves the underwater environment.

Table 2. *Cont.*

Ref.	Year	Author	Key Contribution Summary
[37]	2011	Hürst	Hürst focuses on multimodal interaction concepts for augmented reality applications, exploring how combining multiple forms of input and output can enrich user experiences in a sustainable manner. His work is particularly relevant for museums and urban spaces, where multimodal AR can offer more dynamic and intuitive ways to interact with cultural heritage, enhancing learning and exploration while being eco-friendly.
[38]	2012	Haugstvedt	Haugstvedt investigates the acceptance of mobile augmented reality for cultural heritage exploration, with an emphasis on sustainable technology adoption. Using technology acceptance models, his study identifies key factors influencing the use and adoption of mobile AR, highlighting its potential to transform urban heritage exploration and museum visits into interactive and contextually enriched experiences that are mindful of environmental and cultural sustainability.
[39]	2012	Grasset	Grasset's research on image-based view management for augmented reality browsers offers innovative strategies for presenting AR information more effectively, with a focus on sustainable content delivery. His work enhances user interaction with content and the environment, particularly in museums and urban heritage spaces, by providing more immersive and contextually relevant AR experiences that consider the sustainable use of digital resources.

Initial Development Phase (2013–2018): During this period, publications related to the research topic began to emerge, and although growth was modest initially, it gained greater consistency over time. This phase also began to reflect an increased awareness and incorporation of sustainability in augmented reality applications, particularly in the context of cultural heritage and tourism. A significant increase in the number of publications was observed compared to the initial phase or previous period. In total, 431 publications were identified, representing a substantial number compared to the initial phase. These publications have generated a total of 7923 citations, underscoring the growing importance and interest in the use of augmented reality, especially in the context of applications in museums and cultural heritage, especially in developing sustainable solutions in museums and cultural heritage. This period marked a milestone in the advancement and consolidation of this research area, with a noticeable shift towards incorporating sustainability in augmented reality applications. Throughout this period, several significant contributions of augmented reality to the tourism industry emerged; they are outlined as follows Table 3.

Empowerment Phase (2019–2023): The emergence of COVID-19 has catalyzed the widespread use of various technologies worldwide, and the tourism industry has not been an exception. During this stage, a significant increase in publications related to the use of technologies has been observed, with augmented reality playing a prominent role in this trend while emphasizing sustainable tourism practices. The pandemic forced many people into isolation, leading them to seek new ways to experience tourism and explore places of interest without the need to be physically present. In response, sustainable virtual tourism, supported by augmented reality, emerged as a key solution, enabling eco-friendly access to numerous museums and points of interest worldwide. It was in this context that augmented reality emerged as a key solution, enabling numerous museums and points of interest to be accessible to tourists worldwide, even when they could not visit them physically. This phase also saw advancements in AR technologies focused on reducing carbon footprints and promoting environmental conservation in tourism. During this timeframe, several notable advancements in augmented reality within the tourism sector have surfaced, centered on sustainable and responsible tourism practices, outlined as follows Table 4.

Table 3. Initial development phase (2013–2018).

Ref.	Year	Author	Key Contribution Summary
[40]	2013	Martínez-Graña	Martínez-Graña employs Google Earth and QR codes to create virtual tours, enhancing geological heritage understanding and museum experiences, allowing users to interactively learn about geodiversity in a sustainable and environmentally friendly manner.
[41]	2013	Gimeno	Gimeno develops an AR authoring tool using depth maps, focusing on cultural heritage applications with an emphasis on sustainable digital preservation. This tool enhances museum and GeoCities experiences by creating interactive, educational exhibitions.
[2]	2014	Mortara	Mortara analyzes the application of serious games for cultural heritage, demonstrating their utility in museums and educational settings to improve engagement and understanding of historical and cultural narratives with a focus on sustainable cultural education.
[42]	2014	Ridel	Ridel's 'The Revealing Flashlight' is an interactive AR tool allowing users to uncover detailed aspects of cultural artifacts, thereby enhancing the learning and discovery process in museums and urban heritage in an eco-friendly manner.
[43]	2015	D'Agnano	D'Agnano introduces 'Tooteko', integrating AR, digitization, and 3D printing to create multisensory cultural experiences, with a significant focus on sustainable and accessible cultural interaction. This project enhances accessibility and interaction with cultural heritage, especially in museums and urban settings.
[44]	2015	Bostanci	Bostanci explores the integration of Kinect technology in AR for cultural heritage, enhancing user interaction with museum exhibits and urban heritage through gesture-based engagement and immersive experiences, with an awareness of sustainable technology use.
[45]	2016	Chiabrando	Chiabrando focuses on converting 3D survey data into user-friendly historical building information models (HBIMs), providing detailed and accurate representations of historical buildings for better preservation and understanding, with a sustainable approach to cultural heritage management.
[46]	2016	Skarlatos	Skarlatos highlights the iMARECULTURE project's use of advanced VR and AR to bring Europe's underwater cultural heritage closer to the public, enhancing awareness and accessibility through interactive technologies, with a strong emphasis on sustainable cultural preservation.
[47]	2017	Dieck	Tom Dieck and Jung examine augmented reality's value from stakeholders' perspectives in cultural heritage sites, assessing how these technologies are perceived and can be optimized for better heritage communication with sustainability considerations.
[48]	2017	Jung	Jung and tom Dieck investigate the synergistic application of AR, VR, and 3D printing in cultural heritage, focusing on how these technologies collectively enhance visitor experiences and engagement in museums with a sustainable use of resources.
[1]	2018	Bekele	Bekele offers a broad overview of how augmented, virtual, and mixedreality technologies are applied to preserve and communicate cultural heritage, highlighting their role in enhancing visitor experiences and engagement with a sustainable focus.
[49]	2018	Chung	Chung et al. study the impact of augmented reality in Korean cultural heritage tourism, focusing on how immersive experiences can significantly alter visitor perceptions and engagement with historical sites, with an added emphasis on promoting sustainable tourism practices.

Table 4. Initial development phase (2019–2023).

Ref.	Year	Author	Description of Contribution
[50]	2019	Bec	Bec proposes a conceptual model for managing immersive tourism experiences in cultural heritage with a focus on sustainable practices. This model addresses integrating immersive technologies, heritage preservation, and visitor satisfaction, providing a guide for tourism professionals to enhance planning and management of cultural tourist experiences in an environmentally responsible manner.
[51]	2019	Tzima	Tzima explores educators' perceptions of augmented reality (AR) in educational settings, highlighting its potential for sustainable learning environments. The study highlights opportunities and challenges of AR in education, with implications for enhancing learning in museums and urban heritage sites while considering environmental and social sustainability.
[52]	2020	Graziosi	Graziosi et al. delve into standardization efforts for compressing point cloud data in cultural heritage, focusing on sustainable data management. This work on V-PCC and G-PCC standards is significant for efficiently handling and transmitting voluminous data, influencing the development of immersive experiences in museums and GeoCities with an emphasis on data sustainability and efficiency.
[53]	2020	Trunfio	Trunfio and Campana introduce a visitor experience model for mixed reality in museums, incorporating sustainability in heritage preservation and communication. This model offers insights into enhancing visitor engagement and education about cultural heritage while maintaining sustainable practices.
[54]	2021	Ching	Chin and Wang investigate the impact of augmented reality in a mobile touring system on university students' learning performance and interest, with a focus on sustainable educational methods. Their findings provide insights into augmented reality's benefits in educational settings and its potential to enhance engagement with cultural heritage in museums and urban contexts in an environmentally conscious way.
[55]	2021	Banfi	Banfi examines the evolution of interactivity, immersion, and interoperability in HBIM and its uses with digital models, VR, and AR in built cultural heritage, emphasizing sustainable integration of technology. This work highlights how advancing technologies integrated into HBIM can enhance the cultural heritage experience in museums and urban environments in a sustainable manner.
[56]	2022	Trunfio	Trunfio, Lucia, Campana, and Magnelli focus on innovating the cultural heritage museum service model through VR and AR, with a sustainable approach to visitor experiences. They explore how integrating these technologies enhances visitor experiences and satisfaction, transforming engagement and understanding of cultural artifacts in museum settings and urban heritage while being mindful of ecological impact.
[57]	2022	Skublewska	Skublewska-Paszkowska, Milosz, Powroznik, and Lukasik discuss 3D technologies for preserving intangible cultural heritage, with an emphasis on sustainable digitization practices. This review provides insights into digitizing and safeguarding cultural heritage using 3D technologies, highlighting methods for museums and urban heritage sites to utilize immersive techniques in preservation and communication in an eco-friendly manner.
[58]	2023	Jiang	Jiang highlights how augmented reality enhances tourist experiences at cultural heritage sites by providing additional interactive and informative elements, with a focus on sustainable tourism practices. This work offers insights into the transformative potential of these technologies in enriching visitor interactions and the attractiveness of cultural environments in an environmentally responsible way.
[59]	2023	Zhu	Zhu, Fong, and Gan examine the consequences of postmodern authenticity in augmented reality through the case of a World Cultural Heritage site, addressing AR's influence on heritage perception and experience with considerations for sustainable authenticity maintenance. They address how AR influences the perception and experience of heritage, offering new perspectives on maintaining authenticity and cultural significance in museums and historic urban spaces while integrating sustainable approaches to cultural heritage management.

3.2. Country Analysis

Given that tourism has been severely impacted by the COVID-19 pandemic and the current global economic consequences, numerous publications and applications have emerged worldwide to mitigate the impact on a sector that plays a crucial role in the economies of many regions around the world, while incorporating sustainable practices and strategies. In this context, an analysis of the top ten countries leading in the production of content related to augmented reality applied to the tourism sector with a sustainable approach is presented, as detailed in the table below Table 5.

Table 5. Countries.

Country	Publications (Total and % of Total)	Citations (Total and % of Total)	Publications in Indexed Journals (Quartile Distribution)	Prominent Contribution	Ref.
Italy	271 (23.98%)	2679 (21.35%)	Q1: 42%, Q2: 12% Q3: 23%, Q4: 22%	Botrugno: Developed AR and UAVs for archaeology, enhancing site exploration and presentation with a focus on sustainable archaeological practices.	[60]
Greece	104 (9.2%)	1033 (7.99%)	Q1: 40%, Q2: 29%, Q3: 17%, Q4: 14%	Tzima: Explored AR in education from educators' perspectives, enhancing learning in various settings with an emphasis on sustainable educational methods.	[51]
China	91 (8.05%)	368 (2.93%)	Q1: 39%, Q2: 16%, Q3: 16% Q4: 29%	Chen: Focused on designing serious heritage games for immersive user engagement in cultural heritage with sustainable gaming approaches.	[61]
United Kingdom	66 (5.84%)	1876 (14.95%)	Q1: 52%, Q2: 26%, Q3: 17%, Q4: 4%	Mortara: Addressed cultural heritage learning through serious games, enhancing educational engagement with a sustainable focus.	[2]
Spain	65 (5.75%)	680 (5.42%)	Q1: 55%, Q2: 41%, Q3: 5%	Joo-Nagata: Investigated AR in pedestrian navigation and educational programs, enhancing learning and navigation with sustainable technology integration.	[62]
Germany	40 (3.54%)	435 (3.47%)	Q1: 20%, Q2: 60%, Q3: 20%	Gleue: Designed mobile devices for AR in outdoor environments, improving archaeological site exploration with an emphasis on environmental sustainability.	[18]
Portugal	40 (3.54%)	319 (2.54%)	Q1: 31%, Q2: 31%, Q3: 19%, Q4: 19%	Marques: Focused on 3D models of cultural heritage in AR environments, enhancing immersive representation with sustainable modeling techniques.	[63]
Korea	38 (3.36%)	746 (5.95%)	Q1: 75%, Q3: 17%, Q4: 8%	Chung: Studied AR's role in cultural heritage tourism, transforming visitor interactions with heritage sites, integrating sustainable tourism practices.	[25]
United States	37 (3.27%)	313 (2.49%)	Q1: 54%, Q2: 15%, Q3: 23%, Q4: 8%	Marasco et al.: Examined next-generation virtual technologies in tourism marketing, focusing on cultural heritage promotion with sustainable approaches.	[64]
France	33 (2.92%)	450 (3.59%)	Q1: 67%, Q2: 11%, Q3: 11%, Q4: 11%	Serravalle et al.: Analyzed AR's role in tourism, specifically in museums, from multiple stakeholders' perspectives, with a focus on sustainable cultural engagement.	[65]

Regarding the network analysis, six communities can be identified (see Figure 3) related to this theme, usually led by countries such as the United Kingdom, Italy, Portugal, the USA, and Montenegro. The most prominent community (purple), led by the United Kingdom in collaboration with Australia and the Netherlands, focuses on the importance of augmented reality (AR) in cultural heritage sites from a stakeholder perspective, with an increased focus on sustainable practices in heritage preservation and management. This study investigates how AR technology influences multiple groups involved in the preservation, management, and promotion of cultural heritage. It explores the needs and expectations of stakeholders, including cultural site managers, tourists, local communities, and technology providers. Furthermore, it examines how AR can create value for these stakeholders, whether by enhancing the visitor experience, generating additional tourism revenue, facilitating cultural preservation, or actively engaging local communities in sustainable cultural activities. The authors in this community also address challenges and opportunities related to implementing AR at cultural heritage sites and provide examples of successful case studies, illustrating how this technology has been integrated into visitor experiences at such locations in a manner that is mindful of environmental and cultural sustainability [47].
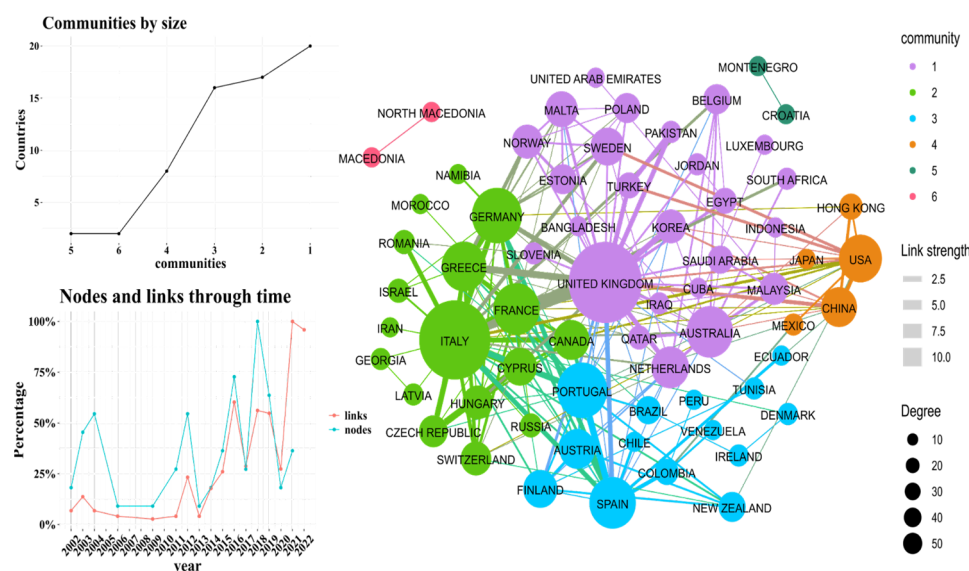

Figure 3. Country collaboration network.

The second community (green), led by Italy with strong collaboration from authors in Greece, France, Germany, and Canada, focuses on the development and evaluation of an augmented reality application called "Svevo Tour", with a significant emphasis on sustainable cultural tourism. This application was created to enhance the visitor experience at a literary museum, specifically at the Italo Svevo Museum in Italy. The article explores how augmented reality is used as a tool to enrich the museum visit and engage visitors more deeply and interactively. It describes the design and development processes of the application, as well as the results of experimentation with real museum visitors. The study highlights how augmented reality can contribute to the promotion of literature and public engagement in a cultural setting, providing a more engaging and educational experience with consideration for sustainable cultural engagement [66].

The third community (blue), led by Portugal with strong ties to Spain and Austria, addresses the topic of communicating cultural heritage through mobile augmented reality applications, with a focus on sustainability in cultural communication. This community demonstrates how mobile augmented reality applications can play a crucial role in communicating and promoting cultural heritage in an environmentally and socially responsible manner. The authors explore how augmented reality technology is used as an effective

tool to enhance interaction between the public and cultural sites, such as museums and historical locations. Additionally, the article analyzes how these applications can enrich the visitor experience by providing additional information, historical contexts, and real-time visual elements through mobile devices in a way that supports sustainable tourism [64]. The fourth community, led by the United States with strong collaborations with China and Hong Kong, investigates the role of next-generation virtual technologies in destination marketing with a sustainable approach. The study focuses on how these technologies, such as virtual reality and augmented reality, are being used in destination marketing. The authors explore how these technologies can create immersive and engaging experiences for tourists, allowing them to explore a destination before their visit. Furthermore, the article examines how virtual technologies can influence tourists' travel decisions and their perception of a specific destination, with a focus on promoting sustainable travel choices [67].

The fifth community (dark green) consists of authors from Montenegro and Croatia, focusing on the valorization and promotion of bridges in Montenegro through the implementation of information and communication technology (ICT) with sustainable practices. The authors explore how ICT can be used to enhance the cultural, historical, and touristic value of bridges in Montenegro. They analyze how the application of these technologies, such as augmented reality or 3D visualization, can enrich the visitor experience by allowing them to explore and learn about the bridges interactively and attractively. Moreover, the community addresses how the promotion of these cultural assets through ICT can contribute to tourism development in the region while considering environmental impacts and promoting sustainable tourism development [68]. The last, fuchsia, community consists of authors from Macedonia and North Macedonia, providing a comprehensive view of how architecture and home design are evolving to address the changing needs and challenges of modern life, with a strong emphasis on sustainability. The editors and contributors explore a wide range of topics related to contemporary housing, from sustainability and energy efficiency to the incorporation of advanced technologies into the home [69].

3.3. Journal Analysis

Below are the top ten journals and conference proceedings (see Tables 6 and 7) for publications in the field of augmented reality applied to museums and GeoCities, focusing on publications that understand the evolution and emphasize the sustainable use of this technology in the cultural and tourism context. These journals represent a valuable source of knowledge and reflect the most relevant trends, research, and developments in this constantly growing interdisciplinary field, with a special emphasis on sustainable practices and eco-friendly approaches. Through this analysis, the aim is to identify the main academic contributions, predominant thematic approaches, and international collaborations driving research and the application of augmented reality in cultural heritage preservation and enhancing tourist experiences in urban environments and GeoCities with sustainable methodologies.

Table 6. Top conference proceedings.

Journal	WoS	Scopus	Impact Factor	H Index	Quantile
Lecture Notes In Computer Science (including subseries *Lecture Notes In Artificial Intelligence* and *Lecture Notes In Bioinformatics*)	0	138	0.32	446	Q3
International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives	0	45	0.27	82	-
ACM International Conference Proceedings Series	0	35	0.21	137	-
ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences	0	23	0.38	48	-
Communications in Computer and Information Science	0	21	0.19	62	Q4
CEUR Workshop Proceedings	0	16	0.2	62	-

Table 7. Top journals.

Journal	WoS	Scopus	Impact Factor	H Index	Quantile
Heritage	18	17	0.34	16	Q1
Journal on Computing and Cultural Heritage	0	19	0.54	31	Q1
Advances in Intelligent Systems and Computing	0	14	0	58	-
Applied Sciences (Switzerland)	0	14	0.49	101	Q2

It is important to note that the vast majority of publications related to this research topic are disseminated through participation in various conferences worldwide. Therefore, *Lecture Notes in Computer Science* (including the subseries *Lecture Notes In Artificial Intelligence* and *Lecture Notes in Bioinformatics*), as an aggregator of conferences in the field of computer science applications, ranks first for conference proceedings, with 138 publications in the Scopus database, with a growing emphasis on sustainable practices in augmented reality applications. The work of Caggianese [70] is highlighted, addressing the topic of natural interaction and augmented reality in the context of enjoying cultural heritage in outdoor conditions. The study focuses on the application of augmented reality technologies to enrich the visitor's experience at outdoor cultural and heritage sites, considering environmental sustainability. The authors explore how natural interaction, i.e., the way people intuitively interact with their environment, can be effectively integrated with wearable augmented reality devices, such as smart glasses. This integration emphasizes sustainable tourism and minimal environmental impact. In the second position of conference proceedings is the *International Archives of the Photogrammetry, Remote Sensing, and Spatial Information Sciences—ISPRS Archives* with 45 publications, representing the second-largest aggregator of conferences related to augmented reality applied to cultural tourism with a sustainable approach. The work of the author Chiabrando [45] stands out, focusing on the creation and handling of 3D models of historical buildings through 3D surveys. The study addresses the sustainable transformation of point clouds generated from 3D scans into digital models used for the management of architectural heritage. The authors explore how these advanced perception and spatial representation technologies can be leveraged to create historical building models with a user-centered approach known as historical building information modeling (HBIM), involving the sustainable and precise creation of digital models.

In the third position of conference proceedings is the *ACM International Conference Proceedings Series* with 35 articles, which publishes the results of various computer-science-related conferences. Among the notable works is that of Střelák [71], which investigates user experiences in the context of a mobile augmented reality tourist guide. The study focuses on evaluating and analyzing how users interact with and experience a tourist guide in which augmented reality is the primary tool, with considerations for sustainable tourism practices. The authors investigate how this technology influences tourists' perception and satisfaction, as well as their overall experience while exploring a tourist destination with an emphasis on environmentally friendly and sustainable tourism. In the fourth position of conference proceedings is the *ISPRS Annals of Photogrammetry, Remote Sensing, and Spatial Information Sciences* with 23 articles, with the publication of Teruggi [72] standing out. This work focuses on the preservation and accessibility of cultural heritage through advanced 3D scanning and semantic enrichment technologies, considering sustainable practices in cultural heritage preservation. The study addresses how to efficiently and accurately perform 3D scans of large cultural heritage sites and structures, followed by enriching these 3D models with semantic data for deeper understanding, and investigates how these enhanced digital representations can facilitate virtual access and the cultural heritage experience for the general public in a sustainable manner. In the fifth position of conference proceedings is the book series by Springer "*Communications in Computer and Information Science*" with 21 publications. The work of Voinea [73] is notable, as it focuses on applying augmented reality technology to explore and enrich cultural heritage. The study is based on the use of platforms like Google's Project Tango and ARCore, which are augmented reality

technologies, to create immersive and educational experiences in cultural and heritage environments, with a focus on sustainable interaction with cultural heritage. The authors investigate how these technologies can enhance the understanding and appreciation of cultural heritage by allowing visitors to interact with additional information and overlaid visual elements in real time through mobile devices.

The "*CEUR Workshop Proceedings*" is in the last position, also serving as a compilation of various conferences worldwide. The publication by Armesto [74] stands out, addressing the monitoring and assessment of structural damage in historic buildings, with a focus on sustainable preservation techniques. The main focus of this research is the use of photogrammetric and monitoring techniques to assess the conservation status of historic buildings and detect possible structural damage while promoting sustainable conservation practices.

In the first position of the top journals is the journal "*Heritage*" with 18 publications in WoS and 17 in Scopus, making it the journal with the highest number of publications on the subject. The work of Karuzaki [75] is highlighted, which focuses on the use of highly realistic virtual human avatars in applications related to cultural heritage, with an emphasis on sustainable digital representation in cultural contexts. The study explores how technology can be used to create digital representations of humans that are as lifelike as possible and to apply these avatars in cultural-heritage-related environments in a way that is mindful of environmental and cultural sustainability. The second position in the top journals is the "*Journal on Computing and Cultural Heritage*", with 19 works in Scopus. One of the most cited works is that of Ridel [42], who focuses on the development and application of interactive spatial augmented reality technology for the detailed exploration of cultural heritage artifacts. The author presents an approach that uses augmented reality to enhance the visitor's experience by allowing them to thoroughly investigate cultural objects and artifacts, considering sustainable methods in cultural exploration and presentation.

In the third position of the top journals is the journal "*Advances in Intelligent Systems and Computing*" with 14 articles, featuring the work of Ramtohul [76], who focuses on the development of a prototype mobile augmented reality system designed specifically for implementation at cultural heritage sites with sustainable technological solutions. The last journal is "*Applied Sciences (Switzerland)*", which has a dedicated section focused on cultural tourism. Among the most cited works is that of Gonzalez [77], which explores the use of augmented reality to improve motivation in learning related to cultural heritage studies. The research investigates how augmented reality technology can effectively motivate students and participants in cultural heritage studies programs while incorporating sustainable learning practices. Overall, these top journals and conference proceedings provide valuable insights into the evolving landscape of augmented reality applications in cultural heritage and tourism, showcasing international collaborations and thematic trends, with a growing focus on sustainability.

Figure 4 illustrates the entire set of communities identified using the Ghosh et al. [10]. algorithm within the journal citation network. A notable tipping point is observed between communities 3 and 4, leading to the selection of the three largest communities for this study, with a particular emphasis on analyzing their focus on sustainability within the augmented reality and cultural heritage sector. The visualization of nodes (representing journals) and links (indicating citations) over time demonstrates the gradual consolidation of these communities. Notably, the proportion of links represented by the orange line surpasses that of the green line, indicating a strengthening of the community since 2017, with an increasing trend towards sustainable practices in research and publication.

When analyzing the communities (see Figure 5) based on their relationship with the citation of scientific articles, three communities can be highlighted. The first community (purple) refers to the citation of articles from conference proceedings which have been cited by significant journals such as *IEEE Development System*. Among them, the work of Skarlatos [46] stands out, addressing the iMARECULTURE project, focused on the use of advanced virtual reality (VR), immersive serious games, and augmented reality (AR) tech-

nologies to promote awareness and access to European underwater cultural heritage with an emphasis on sustainable preservation and public education. The project aims to address the challenges related to the preservation and promotion of submerged archaeological sites and artifacts in a way that engages and educates the public while considering environmental sustainability. The authors emphasize the importance of protecting and showcasing Europe's underwater cultural heritage, which includes shipwrecks, sunken ancient cities, and archaeological remains. These underwater sites are often difficult to access and require innovative approaches to make them accessible to researchers, educators, and the general public. Among other projects funded by Horizon Europe, the BavAR[t] project stands out. It is an augmented reality (AR) game designed to democratize art and culture. This game utilizes innovative AR technologies to offer an interactive and accessible experience to a broad audience, aiming to make art and culture more affordable and appealing to everyone. BavAR[t] allows users to explore art and culture in a unique and immersive way, using their mobile devices to interact with cultural and artistic elements in different settings, both in public spaces and virtual environments. By pointing their devices at specific objects or locations, users can unlock interactive content, stories, and educational experiences related to art and culture. The game is aimed at increasing participation and interest in art and culture, removing barriers that often hinder access to these fields. By offering a playful and educational experience, BavAR[t] seeks to inspire people of all ages and backgrounds, promoting learning and appreciation of cultural and artistic heritage [78].
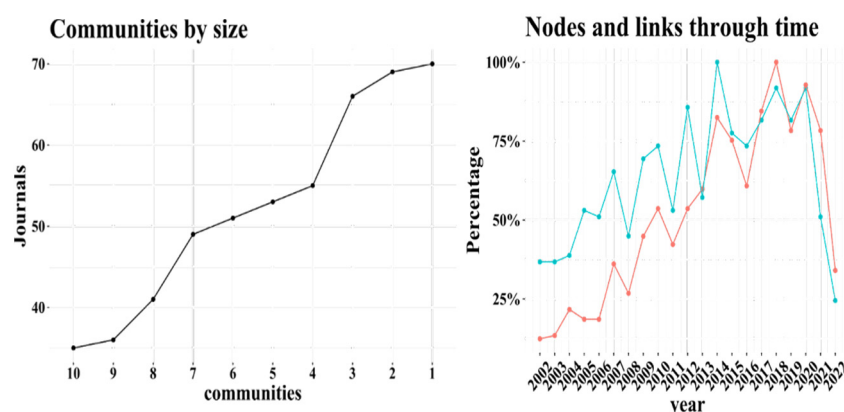

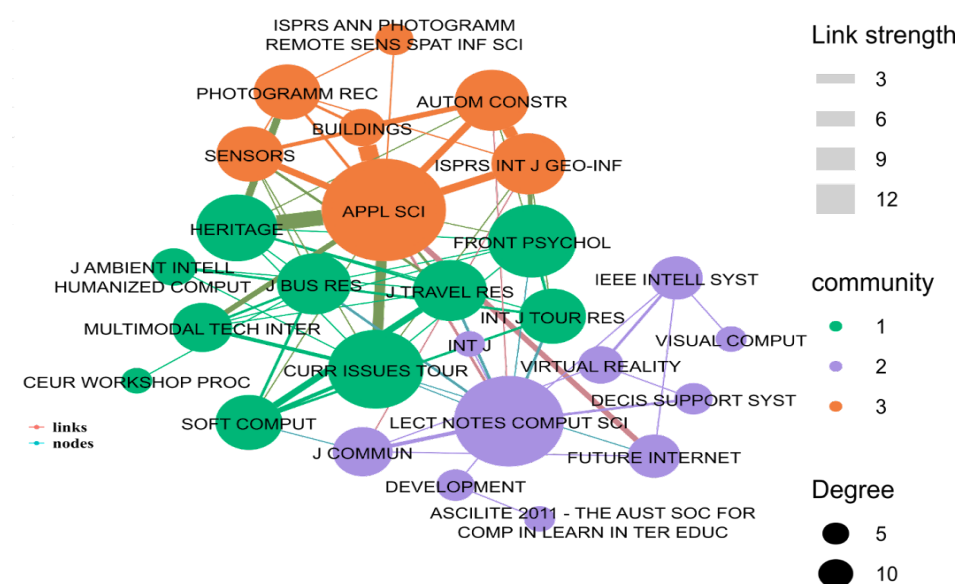**Figure 4.** Community analysis.

Figure 5. Journals collaboration network.

Another project funded by Horizon Europe is "Locative Games for Cultural Heritage", which focuses on the creation and use of location-based games for exploring and learning about cultural heritage with sustainable and interactive methodologies. This innovative project employs location technologies, such as GPS and augmented reality (AR), to create interactive gaming experiences that guide users through sites of cultural and historical importance in an environmentally responsible manner. The main goal of the project is to make cultural heritage more accessible and appealing, especially to younger generations, by fostering education and engagement through a playful methodology. The locative games designed in this project allow participants to immerse themselves in historical and cultural environments, where they can actively and entertainingly learn about history, art, and traditions. Players can explore cities, museums, and historical sites, interacting with game elements that lead them to discover stories, solve puzzles, and complete tasks related to the cultural heritage of the area. These activities not only provide cultural knowledge but also promote the physical exploration of spaces, encouraging users to visit and learn about real places [79].

The "Communities and Artistic Participation in Hybrid Environment" project [80], funded by Horizon Europe, focuses on fostering artistic participation and collaboration in hybrid environments that combine physical and digital spaces, with a strong focus on sustainable artistic practices. This project aims to explore and develop new forms of interaction and artistic expression within communities, using emerging technologies to create inclusive and accessible cultural experiences that are environmentally and socially sustainable. The main objective is to create a space where communities can collaborate, share, and experiment with art interactively, leveraging the possibilities offered by combined digital and physical environments. This involves the use of augmented reality, virtual reality, online platforms, and other digital media to complement and enrich artistic experiences in physical spaces such as galleries, theaters, and public areas. One of the key aspects of the project is its focus on community participation. Community members are encouraged to actively engage in the creative process, from conception to the realization of artistic projects. This not only democratizes the artistic process but also allows for a diversity of voices and perspectives in the creation and appreciation of art. The project also aims to investigate how hybrid environments can overcome geographical and social barriers, enabling people from different regions and backgrounds to participate in collective artistic experiences. This is achieved through the creation of platforms and digital tools that facilitate remote collaboration and cultural exchange.

The second community features a large number of citations from the journal *Current Issues of Tourism*, whose authors have cited works from journals such as *Heritage*. In this community, the focus is on the use of augmented reality (AR) through wearable devices to enhance the learning experience of visitors in art galleries. The authors explore how AR technology can influence visitors' generic learning outcomes, i.e., the educational and cognitive achievements they gain from their experience in an art gallery [81]. Finally, the orange community is led by a strong citation relationship with the journal *Applied Science*, which focuses on the implementation and perception of virtual reality (VR) in the museum context, specifically from the perspective of museum professionals. The research investigates how museum professionals perceive and experience the incorporation of virtual reality into their institutions. The authors analyze the attitudes, challenges, and opportunities that professionals face when adopting VR technologies for the presentation and interpretation of their collections and exhibitions in a manner that aligns with sustainable museum practices and responsible cultural stewardship.

3.4. Author Analysis

The analysis of the top authors (see Table 8) in the field of augmented reality applied to museums and GeoCities is crucial for understanding the trajectory and key contributions in this ever-evolving interdisciplinary field. These authors represent influential voices whose works have made a significant impact on research and the application of augmented

reality in the cultural and tourism context, with a growing emphasis on sustainability. Through this analysis, the aim is to identify the most prominent researchers, their predominant thematic focuses, and their impact on the preservation of cultural heritage and the enhancement of tourist experiences in urban and city environments. Their research and contributions not only drive the advancement of augmented reality technology but also enrich the way museums, cultural sites, and tourist destinations interact with the public, emphasizing sustainable practices and eco-friendly technologies. It is worth noting the significant participation of authors from Italy, which is one of the leading countries in such publications and has shown a commitment to integrating sustainability into cultural and technological advancements.

Table 8. Top ten authors on augmented reality in tourism.

No	Researcher	Total Articles	Scopus Index	Affiliation
1	Pierdicca R	17	24	Università Politecnica Delle Marche, Ancona, Italy
2	De P L	16	17	Università Del Salento, Lecce, Italy
3	Kim J	16	3	Sungkyunkwan University, Seoul, South Korea
4	Frontoni E	15	33	Università Degli Studi Di Macerata, Macerata, Italy
5	Jung T	11	27	Manchester Metropolitan University, Manchester, United Kingdom
6	Liarokapis F	11	24	Extended Experiences Mrg, Nicosia, Cyprus
7	Marto A	11	7	Polytechnic Institute Of Leiria, Leiria, Portugal
8	Woo W	11	27	Korea Advanced Institute Of Science And Technology, Daejeon, South Korea
9	Li Y	10	6	Xi'an Jiaotong-Liverpool University, Suzhou, China
10	Barrile V	9	16	Università Degli Studi Di Reggio Calabria, Reggio Calabria, Italy

The top two authors are from Italy. Pierdicca [82], affiliated with Università Politecnica Delle Marche, Ancona, Italy, leads with the highest number of publications in this domain, totaling 17 articles. His work primarily focuses on eTourism, emphasizing the role of information and communication technology (ICT) in tourism management with environmental considerations. Pierdicca's research delves into how ICT is transforming the tourism industry, including aspects like the influence of social networks, tourism information management, personalized travel experiences, and mobile applications in travel planning and enjoyment. His research integrates sustainable tourism strategies and eco-friendly approaches. De Paolis [83], from Università Del Salento, Lecce, Italy, with 16 published articles, specializes in creating digital simulations that recreate life in medieval towns for educational and promotional purposes in the tourism sector, incorporating sustainable and environmentally friendly methodologies. These simulations aim to provide immersive and educational experiences for visitors, allowing them to explore and gain a deeper understanding of medieval life and culture. This approach serves both educational and tourism promotion purposes, attracting tourists interested in the history and cultural heritage of medieval cities.

The third author, Hayun Kim [84] from Sungkyunkwan University, Seoul, South Korea, has contributed 16 articles focusing on the development of mobile augmented reality applications in cultural heritage sites. Kim's research emphasizes two key aspects, ontology-based information modeling and user studies, with a strong emphasis on sustainable and ethical ontology-based information modeling and user studies. He concentrates on creating ontology-based information models that enable precise semantic representation of cultural heritage sites, enriching the information available to users of mobile augmented reality. Kim also conducts user studies to assess the effectiveness and user experience of mobile augmented reality based on ontologies in cultural heritage contexts. Naspetti [85], who collaborates with the top two Italian authors, Perdicca and De Paolis, specializes in using eye-tracking techniques to enhance augmented reality applications, with a consideration for sustainable user interaction and engagement. The author's work revolves around the auto-

matic analysis of eye-tracking data collected during augmented reality experiences. This analysis aims to optimize and enrich user experiences in augmented reality applications by adapting the presented information based on users' visual interactions. Eye tracking serves as a valuable tool for understanding how users visually engage with augmented reality applications.

Jung T [47], from Manchester Metropolitan University, Manchester, United Kingdom, ranks fifth with 11 publications. His research explores how augmented reality, virtual reality, and 3D printing can collaboratively enhance the visitor experience at cultural heritage sites, with an approach that integrates sustainable practices in visitor engagement. Jung emphasizes the importance of the visitor experience at heritage sites and discusses the concept of "co-creation of value". This concept highlights how visitors can actively contribute to shaping their experiences and perceptions of cultural heritage sites. Augmented reality, virtual reality, and 3D printing facilitate this co-creation by enabling visitors to interact with digital models, historical reconstructions, and physical replicas of cultural artifacts and structures. Bruno [86] from Extended Experiences Mrg, Nicosia, Cyprus, has participated in various collaborations, contributing 11 publications. Notably, he has been involved in the H2020-funded i-MARECULTURE project, which aims to increase awareness and access to European underwater cultural heritage, focusing on sustainable preservation and promotion of submerged archaeological sites and artifacts across Europe.

Marto A [87], from the Polytechnic Institute Of Leiria, Leiria, Portugal, ranks seventh with 11 publications. His notable work includes a comprehensive review of virtual reality and augmented reality applications that incorporate multisensory elements in the cultural heritage context, emphasizing sustainable and immersive interactions with cultural heritage. Marto explores how these advanced technologies create immersive and enriching interactions with cultural heritage, such as museums, historical sites, and culturally significant places. The analysis encompasses applications that go beyond 3D visualization, considering the integration of multisensory elements like sound, touch, and even scent to enhance visitors' immersive experiences. Shin [88] from the Korea Advanced Institute of Science and Technology, Daejeon, South Korea, also boasts 11 publications. One of his noteworthy contributions is the narrative design of a location-based augmented reality game called "Rediscovering Daereungwon", which investigates how narrative design influences players' experiences in location-based augmented reality games, where physical locations are integral to the gameplay, with a focus on sustainable cultural engagement and education.

Li Y [89], from Xi'an Jiaotong-Liverpool University, Suzhou, China, occupies the ninth position with 10 publications. His research primarily focuses on multi-user interaction with virtual reality and augmented reality technologies in the context of cultural heritage objects. Li addresses how to effectively combine both VR and AR to create interactive experiences that allow multiple users to collaboratively explore and learn about cultural heritage objects addressing the effective combination of VR and AR for sustainable and interactive exploration of cultural heritage. This research explores how the synergy of VR and AR enhances the understanding and appreciation of cultural objects, such as historical artifacts, sculptures, paintings, or other elements of cultural heritage. Multi-user interaction is a key aspect of the study, enabling multiple individuals to participate simultaneously in experiences, particularly relevant in museum and historical site settings. Barrile V [90], from Università Degli Studi Di Reggio Calabria, Reggio Calabria, Italy, focuses on the integration of geomatics methodologies in creating cultural heritage applications using augmented reality (AR). The author describes how geospatial and geodetic technologies can capture precise data related to cultural heritage, which can then be used to develop augmented reality applications that enhance user experiences when exploring and learning about cultural heritage. The described geospatial methodologies are utilized to collect high-precision geodetic and georeferenced data from cultural heritage sites and objects. These authors collectively contribute to advancing the field of augmented reality in the cultural and tourism sectors, addressing a wide array of topics and applications. Their research has

a significant impact on how technology enhances our understanding, preservation, and engagement with cultural heritage and historical sites.

Regarding the collaborative work behavior among authors (see Figure 6), it is worth highlighting authors who lead five significant communities related to the study topic. The first community (purple) is led by a strong collaboration alliance between the authors Liarokapis and Barrile, from Cyprus and Italy, who have developed various applications in cultural locations worldwide using disruptive technologies. Their work notably incorporates sustainability by focusing on the sustainable use of digital technologies in cultural heritage conservation. Among the highly cited publications, there is a standout project of a virtual museum. The authors present an innovative proposal in which they use advanced technology, such as virtual reality and augmented reality, to virtually recreate a physical museum, in this case, the Herbert Museum in Coventry, United Kingdom. This project is distinguished by its sustainable approach to digital heritage, minimizing physical impact on the actual museum site. The Herbert Museum is known for its focus on the history and culture of Coventry, and the project aims to bring this experience to a wider audience through digital media. The authors address how they have designed and developed an interactive virtual museum that allows visitors to explore the museum's exhibits and content from anywhere in the world using digital technology [91].
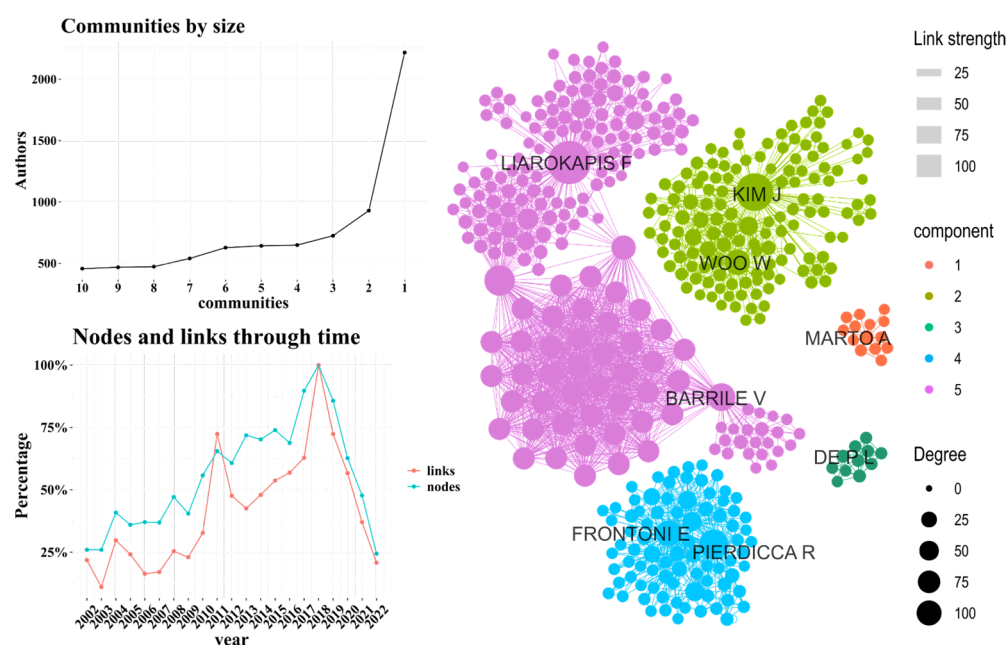

Figure 6. Author collaboration network.

The second community (light green) is focused on collaborations by authors from South Korea, Kim J and Woo W [92], who concentrate on creating and describing a metadata schema specifically designed for augmented reality (AR) applications in the field of cultural heritage. The authors, Kim, Kim, and Woo, highlight the sustainable management and preservation of digital data in cultural heritage applications. They address the need to develop a metadata system that allows efficient integration of AR into the context of cultural heritage, including museums, historical sites, and places of cultural significance. Their approach underlines the importance of sustainable practices in digital archiving and preservation. The third community (blue) is led by the Italian author Clini [93], who focuses on how to harness high-resolution technology and real-time processing capabilities to create immersive and enriching AR experiences in practical applications. The author details the process of acquiring high-resolution images, which may include techniques such as high-definition photography and photogrammetry to capture objects, locations, or scenarios accurately and in detail to superimpose virtual content coherently and precisely

into the real world. This community emphasizes the role of sustainable technology in enhancing cultural experiences without causing detrimental effects on physical sites. This can have applications in various fields, including cultural heritage, education, tourism, and more. The fourth community (dark green) and the fifth community (orange) are focused on the related works of authors De Paoli and Marto, who have leveraged the full potential of augmented reality with a strong focus on the sustainability of cultural dissemination and education.

4. Tree of Science

The tree of science, as conceptualized by Robledo et al. in 2014 [9], serves as a valuable tool for understanding the evolution and structure of academic disciplines through the lens of citation networks; see Figure 7.
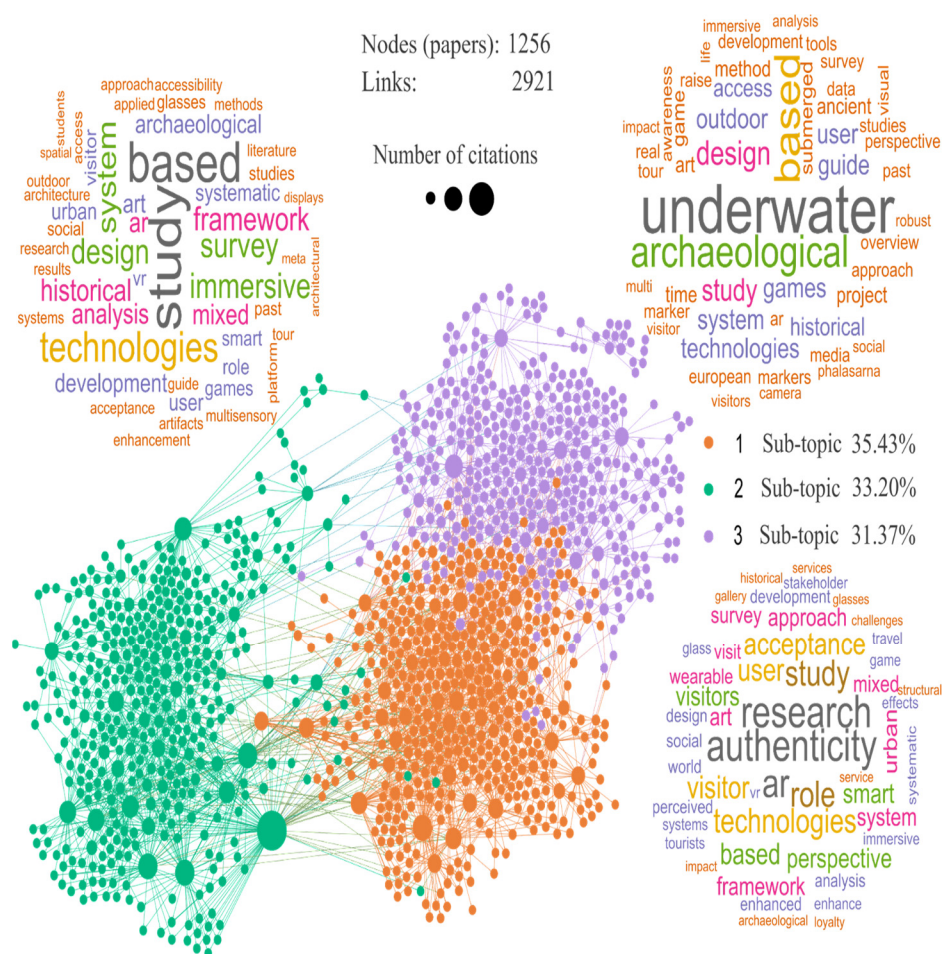
Figure 7. Citation network.

4.1. Root

The application of augmented reality (AR) in museums and GeoCities represents a fascinating convergence of digital technology and the preservation of cultural heritage. This interdisciplinary field is based on overlaying digital information and real-time visualizations in the physical environment, enriching the experiences of visitors and users by providing historical contexts, enhanced narratives, and unique educational opportunities. Moreover, this approach aligns with sustainable practices in cultural heritage, minimizing physical alterations to historical sites while providing rich, interactive experiences. To thoroughly understand this exciting area of study, it is essential to consider the theoretical foundation and practical contributions of researchers and pioneering projects. In this regard, the works by Vlahakis in the years 2001 and 2002 and Azuma in 1997 offer a solid

theoretical foundation, as well as concrete examples of AR implementation in cultural and archaeological sites. These articles emphasize the sustainability of AR in preserving the integrity and authenticity of cultural heritage. These articles not only explore the principles and challenges of AR but also demonstrate how this technology has transformed the interaction with cultural heritage and the way visitors experience museums and GeoCities.

The articles by Vlahakis [94,95] provide a solid theoretical and practical foundation for the application of augmented reality in the context of museums and GeoCities. These articles underscore the sustainable potential of AR in cultural heritage, offering environmentally friendly alternatives to traditional restoration and preservation methods. These works present real-world results and experiences of augmented reality application in the preservation and promotion of cultural heritage. The authors discuss how augmented reality can enhance the visitor experience by allowing them to overlay digital information and real-time visualizations onto the physical environment of a cultural site. Furthermore, the articles delve into the sustainable aspects of AR, such as reducing the need for physical infrastructure and conserving resources.

Likewise, Azuma's article [96] is a fundamental read that provides a comprehensive overview of augmented reality as a field of study. Azuma explores the fundamental concepts, technological approaches, and potential applications of augmented reality. This review aids in understanding how AR can be employed sustainably, reducing environmental impact while enhancing cultural experiences. Together, these articles offer a solid foundation for understanding key concepts, challenges, and opportunities related to the application of augmented reality in museums and GeoCities. They provide concrete examples of how technology can enhance how people interact with cultural heritage and enrich tourist experiences in urban environments and historical sites. These pioneering studies lay the groundwork for the future development of sustainable augmented reality applications in the realms of culture and tourism.

Other authors provide fundamental insights into the application of augmented reality in museums and GeoCities for heritage preservation and communication. These studies highlight the role of AR in sustainable heritage communication, utilizing digital means to preserve and share cultural narratives. The work of Lee et al. [97] demonstrates how immersive e-learning systems based on augmented reality can enrich the virtual experience in museums, which is crucial for heritage communication. Meanwhile, Lu et al. [35] address technical aspects such as the handling of occlusions in outdoor augmented reality environments, relevant for their effective implementation in GeoCities and museums. These studies emphasize the importance of sustainable and responsible use of AR in heritage sites. Kolstee and Van Eck [98] provide a practical perspective on enhancing the museum visitors' experience through augmented reality, while Laroche et al. [99] highlight how this technology can improve the understanding and visualization of heritage. Their work underscores the minimal environmental impact of AR, promoting sustainable cultural exploration. Haugstvedt and Krogstie [38] contribute to the analysis from the perspective of technological acceptance, essential for the successful implementation of these solutions in heritage contexts. Finally, Damala and Stojanovic [100] examine the motivations and needs of cultural heritage professionals, offering insights on adapting augmented reality to improve heritage communication. This adaptation is pivotal in ensuring that AR technologies are used in a manner that respects and sustains the cultural and historical integrity of heritage sites. Together, these studies offer a valuable framework for understanding the impact and possibilities of augmented reality in heritage preservation and communication in museums and urban environments. They collectively underscore the importance of integrating sustainability into the development and application of AR in cultural heritage, ensuring that these technological advancements contribute positively to the preservation and appreciation of our shared history.

4.2. Trunk

At the intersection of digital technology and cultural heritage preservation, augmented reality (AR) in museums and GeoCities emerges as an innovative and promising field. This interdisciplinary discipline focuses on overlaying digital and visual elements onto the physical environment, thus enriching the experiences of visitors and users with historical contexts, immersive narratives, and unique educational opportunities. Incorporating sustainability, this technology enables the preservation of physical sites while offering enhanced interactive experiences, significantly reducing the ecological footprint associated with traditional preservation methods. In this context, numerous authors provide a solid theoretical foundation and practical examples of implementing augmented reality in cultural and archaeological contexts. These studies not only analyze the principles and challenges of augmented reality but also demonstrate how this technology has transformed interactions with cultural heritage, revolutionizing how visitors explore museums and GeoCities in a more sustainable and environmentally friendly way.

Authors like Fenu and Pittarello in 2018 [66], Bekele and Champion [101], and Trunfio, Jung, and Campana [102] are considered integral to the core structure in the metaphorical tree of science and development of augmented reality as applied to museums and GeoCities. Their research emphasizes the role of AR in sustainable cultural engagement, offering alternatives that minimize physical wear on historical artifacts and sites. Just like the trunk of a tree, these works provide essential knowledge and a solid foundation for the growth and expansion of augmented reality in the cultural heritage context. The article by Fenu and Pittarello [66] serves as a solid base, akin to the sturdy core of a tree trunk. It explores the design and experimentation of an augmented reality application to engage visitors in a literary museum. This work lays the groundwork for immersive and engaging augmented reality experiences within museums, emphasizing the importance of user engagement and interaction. The study by Bekele and Champion [35] acts as a critical component of the trunk, much like growth rings within a tree. Their comparison of immersive realities and interaction methods for cultural learning in virtual heritage provides valuable insights into the effectiveness of different approaches. It contributes to the growth in knowledge about how various immersive technologies can be leveraged for educational and cultural purposes.

The research by Trunfio, Jung, and Campana [102] forms a vital section of the trunk, like branches extending from the central support structure of a tree, illustrating how AR can be integrated sustainably into cultural institutions. Their exploration of mixed-reality experiences in museums, including the impact of device functionality on visitor experiences and behaviors, expands our understanding of how augmented reality can be effectively integrated into cultural institutions. This work contributes to shaping the direction of augmented reality development in museums and GeoCities. Together, these articles, like interconnected components of a tree trunk, provide a solid and comprehensive foundation for the growth and evolution of augmented reality applications in the field of cultural heritage. They support the development of this technology and its potential to enhance visitor experiences, promote cultural learning, and contribute to the sustainable future of museums and GeoCities.

Expanding this vision, augmented reality in museums and GeoCities not only enhances the visitor experience but also opens new possibilities for interaction and learning. AR applications can take visitors on journeys through time and space, allowing them to see reconstructions of historical events or visualize how artworks looked in their original context. Additionally, AR can personalize the visitor experience, offering tours and explanations tailored to their specific interests and level of knowledge. In the realm of GeoCities, AR offers a unique opportunity to revitalize urban spaces with layers of historical and cultural significance. Through AR applications, the sustainability of urban heritage can be enhanced, allowing for the conservation of physical spaces while adding digital layers of information and interaction.

Moreover, augmented reality plays a crucial role in education and awareness about cultural heritage. It serves as a sustainable educational tool, reducing the need for physical materials and travel to historical sites, thereby minimizing environmental impact. It can be a powerful tool for schools and educational programs, providing a more dynamic and interactive way to teach history and culture. Students can experience cultural heritage first-hand, which can significantly increase their interest and understanding. The development of augmented reality in museums and GeoCities is not just a matter of technology but also of creativity, narrative, and cultural engagement. As these technologies continue to evolve, they offer sustainable ways to interact with and experience cultural heritage, opening new doors to understanding and appreciating our shared history and culture.

In the context of using augmented reality for the preservation and communication of heritage in museums and GeoCities, several prominent studies provide valuable insights. Barba's [103] study at ISMAR-MASH'D, for instance, underscores the sustainable aspects of mixed-reality walking tours in heritage preservation. Morales, Oishi, and Ikeuchi [104], in their presentation at ISMAR, contributed a technical approach to aerial perspective rendering in mixed reality, relevant for heritage visualization in outdoor settings. This approach highlights the reduced environmental impact of virtual reconstructions compared to physical alterations. Oh, Kim, Nam, and Shi [105], at ISMAR-Adjunct, through their interactive art based on cultural heritages, illustrated how user interaction can enrich the heritage experience. Golodetz, also at ISMAR-Adjunct, contributed to the field with their study on collaborative large-scale 3D reconstruction, crucial for the digital documentation of heritage in a sustainable manner. Finally, Anastasovitis [106] and Roumeliotis [107] presented at ISMAR-Adjunct a vision for creating immersive cultural exhibitions, demonstrating how augmented reality can transform museum experiences. Each of these works significantly contributes to the scientometric analysis of the main article, offering a variety of perspectives on the application of augmented reality in the field of cultural heritage, with a strong emphasis on sustainable practices.

4.2.1. Branch 1: Studying User Acceptance of Smart Technologies in Museums: A Research Perspective on Authenticity and Visitor Experience

This branch represents an essential direction in contemporary research concerning the interaction between technology and cultural heritage. In an increasingly digitized world, museums and cultural sites have adopted smart technologies like augmented reality (AR) to enhance visitor experiences. These technologies are also being explored for their potential in sustainable museum practices, such as reducing the need for physical resources and enabling virtual visits, thereby reducing the environmental impact of museum operations. This research trend focuses on understanding how users perceive and accept these technologies, specifically emphasizing two key aspects: authenticity and the visitor experience. Authenticity pertains to how technology can enhance or influence the perception of authenticity in cultural experiences, while the visitor experience relates to how these technologies shape how visitors interact with and engage in cultural heritage. An additional layer of this research explores the sustainability aspect of these technologies in preserving cultural heritage while minimizing physical alterations and wear on the actual artifacts. Through a review of recent studies and projects, this research perspective seeks to shed light on how smart technologies are shaping the relationship between museums, visitors, and cultural authenticity in the digital age.

Articles [108,109] play a crucial role in advancing trends in user acceptance of smart technologies in museums, providing a research perspective that highlights authenticity and the visitor experience. These articles also consider the sustainable impact of AR in museums, such as energy efficiency and reducing the carbon footprint associated with traditional museum visits. Article [108] offers an interdisciplinary view of co-authorship networking, contributing to understanding how augmented reality (AR) influences human behavior. The study also examines the sustainability benefits of AR, like its role in conserving physical artifacts and reducing the need for travel to cultural sites. The study

in [109] about enhancing the tourist experience through the application of AR in Penang's street art showcases how technology can enrich the authenticity of the visitor experience. It also highlights how AR can be used sustainably to protect and preserve outdoor art installations. Ref. [110] delves deeper into the authenticity perspective in AR marketing at world cultural heritage sites, providing valuable insights into how authenticity impacts user perception in this context. This study further explores how AR can be a sustainable tool in heritage conservation, offering virtual experiences that reduce wear on physical sites. Together, these studies significantly contribute to the development of a more comprehensive understanding of user acceptance of smart technologies in museums and the visitor experience, with authenticity as a key aspect of the interaction between technology and visitors.

Li and colleagues' work [111] focuses on the development and evaluation of a virtual museum prototype enriched with augmented reality, which is essential for understanding user acceptance of smart technologies in museums. Their research on CubeMuseum provides valuable data on how the implementation of augmented reality can enhance the visitor experience and the perception of authenticity in museums. This study is particularly relevant for exploring how new technologies alter and improve the visitor experience, offering an empirical basis for understanding user acceptance and expectations regarding emerging technologies in the museum context.

4.2.2. Branch 2: Underwater Technology Gaming Systems for Archaeological Design and User Guidance in Outdoor Submerged Sites

This branch represents a fascinating convergence of digital technology, archaeology, and the exploration of outdoor underwater environments. In a world where technological advancements continue to transform how we investigate and experience underwater cultural heritage, this area of study emerges as an innovative and promising field. These underwater-technology-based gaming systems not only promise to revolutionize the way submerged archaeological sites are designed and interacted with but also have the potential to enhance the experience of users and visitors sustainably, reducing the environmental impact on these delicate underwater ecosystems. To gain an in-depth understanding of this exciting topic, it is essential to explore the body of research and projects that support the development of these systems, addressing both technological aspects and the user experience in outdoor underwater environments.

The articles [112,113] and the work by VEGA, GAETAN, and MARTIN [66] strongly support the development of this theme. These works offer valuable insights into how immersive and augmented reality technologies can be effectively and sustainably applied in the field of underwater archaeology and user guidance in outdoor environments, minimizing physical disturbances to these sites. The article by VEGA, GAETAN, and MARTIN [114] provides fundamental guidelines on user experience in augmented-reality-based cultural tourism applications, which is directly relevant to the creation of sustainable underwater gaming systems. On the other hand, the article by Formanek, Filip, and Hnat [112] focuses on the comparison of modern and traditional ways of perceiving information about cultural heritage objects, shedding light on how modern technologies can enhance users' understanding and experience in underwater archaeological environments in a manner that respects the integrity of these sites. Furthermore, the work by Trunfio, Campana, and Magnelli [113] explores hybrid reality in cultural heritage reconstruction, which is essential for sustainable archaeological design and user guidance in outdoor underwater sites. Together, these studies support the advancement and effective implementation of underwater-technology-based gaming systems in underwater archaeological contexts, providing key insights into sustainable user experience and design strategies.

The work of De Bonis et al. [115], titled "A Literature Review of User Studies in Extended Reality Applications for Archaeology", presented at the 2022 IEEE International Symposium on Mixed and Augmented Reality, provides a comprehensive analysis of how extended reality applications have been used in archaeological studies. This literary review

contributes to the main article by offering a deep understanding of current practices and the potential of extended reality in archaeological contexts, emphasizing the sustainable aspects of these technologies. On the other hand, the study by Lohfink et al. [116], "Learn Spatial! Introducing the MARBLE-App—A Mixed Reality Approach to Enhance Archaeological Higher Education", presented at ISMAR-Adjunct 2022, explores the use of mixed reality in higher archaeological education. This innovative approach provides valuable insights into how mixed-reality technologies can be applied sustainably to improve understanding of and interaction with submerged archaeological sites, which is directly relevant for the design and user guidance in underwater gaming systems for archaeological sites.

4.2.3. Branch 3: Studies Based on an Immersive Design Technology System for Historical Analysis in a Mixed-Reality Framework

The branch represents a continuously growing research field exploring the potential of immersive and mixed-reality technologies for the analysis and interpretation of history and cultural heritage. Incorporating sustainability, these technologies are recognized for their minimal physical impact on historical sites while providing enhanced interactive experiences. In an increasingly digitized world, these technologies play a pivotal role in how we understand and experience the past. The convergence of virtual reality, augmented reality, and other immersive technologies has opened new possibilities for exploring historical environments and interacting with objects and places from the past, while preserving the integrity and sustainability of these cultural assets. To delve deeper into this exciting topic, it is essential to examine the body of research and projects shaping this field, exploring how these technologies are transforming how researchers, students, and the public engage with history and cultural heritage within a mixed-reality context.

Articles [117–121] are crucial in advancing the theme. These studies particularly emphasize the sustainable aspect of mixed-reality applications in cultural heritage, such as reducing the wear and tear on physical artifacts and sites. In this ever-evolving research field, these studies highlight the diverse applications of immersive and mixed-reality technologies in the realm of cultural heritage and historical analysis. Marques, Pedro, and Araújo's article [117] conducts a systematic literature review of gamification in the context of cultural heritage. This review also addresses the sustainable practices in gamifying heritage experiences, reducing the ecological footprint of traditional tourism. Through this review, the authors shed light on how gamification, often involving elements of mixed reality, has been used to enhance visitors' experiences at cultural and archaeological sites. This study underscores how immersive technologies can be effectively implemented to engage a broader audience and enhance the understanding of historical heritage.

Innocente, Ulrich, Moos, and Vezzetti's work [118] presents a framework study on the use of immersive XR (extended reality) technologies in the cultural heritage domain. Their study also examines the sustainability of using XR in cultural heritage, such as preserving resources and enhancing digital accessibility. The study provides an overview of how these technologies are being employed in the preservation, documentation, and presentation of cultural sites and objects. Moreover, it emphasizes the importance of an immersive approach to historical analysis, as it can enable researchers and visitors to explore historical environments more deeply and interactively.

Süvari, Okuyucu, Çoban, and Eren Tarakci's article [119–121] focuses on the virtual reconstruction of cultural heritage components that have disappeared using augmented reality technology. The study highlights the role of AR in sustainably reconstructing and preserving lost cultural elements, thereby avoiding the need for physical reconstructions that might affect the sites. This immersive application allows researchers and the public to interact with these lost cultural components and engagedly explore their historical context. Collectively, these studies provide a solid foundation for developing research in the field of immersive and mixed-reality technologies for historical analysis in the context of cultural heritage. They demonstrate how these technologies are being leveraged to

enhance visitor experiences, preserve and reconstruct cultural elements sustainably, and enrich our understanding of history and cultural heritage.

The study by Xu, N. [122] and colleagues, focusing on user retention of mobile augmented reality for cultural heritage learning, presented at ISMAR-Adjunct 2022, provides crucial insight into how mobile augmented reality can be used to foster long-term engagement with cultural heritage learning. This research also underscores the sustainability of mobile AR in facilitating widespread access to cultural education, reducing the need for physical travel to historical sites. Meanwhile, Gutkowski, N. et al. [123], in their study on designing historical tours for wearable augmented reality, provide valuable insights into how augmented reality can be used to enrich the experience of historical tours, highlighting the potential of AR in offering sustainable and less intrusive means of exploring historical sites.

The work of Carnevale, L. et al. [124], which explores the use of augmented reality in creating new functions for cultural heritage within an ambient intelligence environment, offers an innovative perspective on how augmented reality can be integrated into museum settings to enhance visitor experience and provide new contexts for historical analysis. Their work also explores the sustainable integration of AR in museums, enhancing visitor experiences without the physical alteration of exhibits. Finally, Zhang, Q. et al. [125] in their study on enhancing the experience of rock painting tours with outdoor augmented reality, presented at ISMAR-Adjunct 2019, contribute a practical application of how augmented reality can be used to enrich the educational experience at historical sites, which is crucial for the development of immersive technologies in the study of heritage. This study also addresses the sustainability of using AR in outdoor settings, offering a non-invasive method to experience and learn about rock paintings without causing damage to these fragile historical artifacts.

5. Conclusions

The application of hybrid immersive technologies, such as augmented reality (AR), in museums and GeoCities has marked a significant advancement in the preservation and communication of cultural heritage. This interdisciplinary field integrates sustainability by offering non-invasive methods to explore and interpret cultural sites, reducing the physical impact on these valuable spaces. This field has profound theoretical and practical implications, inherent challenges, and a promising future research agenda that spans multiple disciplines, including humanities, economics, urban studies, geography, sociology, anthropology, pedagogy, and STEM. The application of augmented reality (AR) in the humanities offers a novel theoretical perspective and practically transforms the visitor's experience by providing a richer context and deeper connection with cultural heritage. From a sustainability standpoint, AR helps preserve resources and energy by reducing the need for physical infrastructure and travel to cultural sites. From an economic standpoint, AR promises to renew the economic models of museums and historical sites, enhancing tourism and generating new employment and development opportunities, especially in the technological and tourist sectors. Additionally, it offers a sustainable approach to cultural tourism, minimizing ecological footprints while providing economic benefits. In urban studies and geography, AR theoretically changes our understanding of urban space by adding layers of historical and cultural information, and in practice, it has the potential to sustainably revitalize and recontextualize urban spaces, turning them into living canvases of history and culture.

From a sociological and anthropological perspective, AR theoretically challenges and expands our understanding of social and cultural interaction, and in practice, it democratizes access to cultural heritage and promotes a greater intercultural understanding, though it also raises questions about cultural authenticity and representation. In pedagogy, AR offers a sustainable approach to education, reducing the environmental impact associated with traditional learning resources. In the STEM disciplines, AR drives innovation in science and technology, with significant practical implications in fields such as computer

science, engineering, and data visualization, requiring the continuous development of advanced software and hardware. This development also includes the challenge of creating environmentally sustainable technology. Collectively, these theoretical and practical implications highlight the transformative potential of AR in the preservation and communication of cultural heritage, paving the way for future research and applications across a variety of fields.

In the realm of applying immersive technologies like augmented reality, some significant limits and challenges must be addressed to ensure the success and integrity of these initiatives. A critical aspect is the sustainable use of technology, ensuring that digital solutions are environmentally friendly and responsibly managed. Ensuring that digital reconstructions are accurate and respect the original context is essential for maintaining the integrity of the cultural heritage that is sought to be preserved and communicated. Achieving this requires close and careful interdisciplinary collaboration among technologists, historians, archaeologists, and other cultural heritage experts, working together to ensure that digital representations are faithful and respectful to the sources. Another significant aspect is the sustainable development of technological accessibility. For immersive experiences to fulfill their potential to educate and enrich a broad audience, they must be accessible to a wide range of the population, including those with economic or physical limitations. This involves not only the availability of the technology itself but also the sustainable design of interfaces and experiences.

The future research agenda in the field of immersive technologies such as augmented reality (AR) presents several key areas that need attention. First, the sustainable development of inclusive technology is crucial. Research is needed on how to make AR and similar technologies more accessible and affordable for various population groups, ensuring that everyone can benefit from these innovations. In addition, assessing the long-term sustainability impact of AR in areas such as heritage education and visitor experience is fundamental. Understanding how these technologies change the way we interact with culture and learning can guide future improvements and should also include a sustainability perspective. Finally, addressing ethical issues related to cultural representation and authenticity in virtual environments is crucial. Ensuring that digital representations are respectful and accurate is vital to maintaining integrity and respect for cultural heritage in the digital age. Together, these areas of research outline a path to a future where immersive technology is used ethically, inclusively, and effectively to enrich our understanding and appreciation of cultural heritage.

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