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Conservation and Protection Treatments for Cultural Heritage: Insights and Trends from a Bibliometric Analysis

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Abstract: Cultural heritage is a fundamental part of the society's identity, and its conservation is of great relevance as it transcends time and memory. To minimize its deterioration, cultural heritage has traditionally undergone diverse preservation and maintenance treatments, and the attention of researchers to developing new and innovative methods for state diagnosis and protection treatments has been increasing in the recent decades. Despite extensive efforts in preservation, there remains a need for comprehensive and systematic mapping of scientific research to identify emerging trends and innovations in the field. To address this gap, in this study, a literature review using a bibliometric analysis and LDA methodology was conducted to systematically map scientific research outputs on cultural heritage conservation and protection. Data were retrieved from the Scopus database, and the annual publications, countries, most-cited publications, authors, institutions, and keywords have been comprehensively analyzed, leading to the detection of research trends and contributing to the existing knowledge in the field. The findings show an increasing number of studies in this field in the last decades, particularly since 2010. Italy, home to the largest number of UNESCO heritage sites, is the most prolific country. Most of the studies are related to metal, paper, and stone as substrates to be protected. Significant progress has been made in understanding the deterioration processes through precise diagnosis and the development of innovative treatments for protection. In this sense, the latest trends have been detected, such as the use of non-invasive techniques for diagnosis and the use of nanotechnology and nature-based treatments for conservation treatments.

Keywords: cultural heritage; conservation; protection; preservation; treatment; bibliometric analysis; scientific mapping; LDA

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1. Introduction

Since the formulation and adoption of the World Heritage Convention in 1972 [1], the preservation and conservation of cultural heritage have attracted worldwide attention. In this sense, scientific research plays a crucial role, driven by a commitment to preserving the world's diverse cultural legacy for future generations [2]. Furthermore, cultural heritage must be contextualized and integrated with a holistic perspective with synergies and collaboration across multiple disciplines to guarantee the prosperity of interdependent natural, social, and economic systems.

Over the past few decades, significant progress has been made in understanding the complex processes involved in the deterioration of tangible cultural heritage. UNESCO [3] categorizes cultural heritage into two main types: tangible and intangible. Tangible cultural heritage is further classified into immovable (historical buildings, monuments, and archaeological sites) and movable categories (paintings, sculptures, furniture, and wall paintings). Nowadays, there is a growing interest in the development of different treatments for the conservation and protection of different invaluable assets of tangible cultural heritage.

However, addressing the main challenges in cultural heritage preservation requires a multifaceted approach, beginning with a precise diagnosis followed by an adequate treatment, typically involving cleaning, consolidation, and protection processes [4,5].

In order to achieve a good diagnosis, it is necessary to firstly understand the mechanisms of deterioration. Various factors contribute to the degradation, including environmental conditions, biological agents, and human activities [6–8]. In recent years, there has been a proliferation of diagnostic technologies that have revolutionized the field of cultural heritage conservation. Advanced analytical techniques, preferably non-destructive, have been employed to analyze the composition and condition of heritage materials without causing harm [9,10]. These technologies provide invaluable insights into the structural integrity of heritage structures and facilitate the early detection of potential risks.

The development of innovative conservation treatments is another area of active research in cultural heritage preservation [11]. Traditional conservation methods have often involved invasive interventions that could alter the original integrity of the heritage. However, recent advancements have led to the emergence of minimally invasive techniques that prioritize authenticity while effectively mitigating deterioration. Nanotechnology, for example, has opened new possibilities for the consolidation and protection of cultural heritage materials, offering enhanced durability without compromising aesthetic value [12–17].

In this context, the existing scientific literature in the field of conservation and protection of tangible cultural heritage offers numerous reviews and articles. However, as the volume of information is broad for a manual review, bibliometric analysis can help to effectively manage the information. Bibliometric analysis has emerged as a powerful tool for evaluating and understanding scientific literature and academic productivity [18]. By quantifying various aspects of research output, such as citation patterns, publication trends, and collaboration networks, bibliometric analysis provides valuable insights into the dynamics of scientific knowledge. In this sense, bibliometric analysis offers a data-driven approach to understanding the landscape of a specific research field. Moreover, bibliometric analysis are interesting sources of data and can help in the decision-making processes for policies and fundings, as quantitative measurements are more easily compared than peer opinions of traditional reviews [19].

In this article, a comprehensive bibliometric analysis of scientific articles related to the conservation and protection of cultural heritage is presented, shedding light on the most prominent research trends.

2. Methods

2.1. Data Collection

Data for this study were collected from the Scopus database using a combination of different search terms to find publications, as can be observed in Figure 1. The Scopus database offers broader coverage of the literature, providing around 20% more than Web of Science and more accuracy than Google Scholar [20]. The combination of search words was considered for the titles, abstracts, and keywords (TITLE-ABS-KEY), and the results were filtered by subject area (Materials Science, Arts and Humanities, etc.), excluding areas out of the scope. The dataset was retrieved on 27 December 2023 as a comma-separated value format (.csv) file, and it was composed of 1501 documents, including articles, reviews, conference papers, books, and book chapters. The dataset included documents published in the period of 1990–2023.

It is worth noting that the present analysis focuses on English peer-reviewed documents and that time period was selected because 1990 is the first year in which a publication appeared according to the search criteria established by the authors. Moreover, the areas considered in the scope are those whose had more than 100 documents in the field: *Materials Science, Engineering, Arts and Humanities, chemistry, Social Sciences, Physics, Environmental Science, Computer Science, and Chemical Engineering*. It is important to acknowledge these limitations in order to better interpret the obtained results.

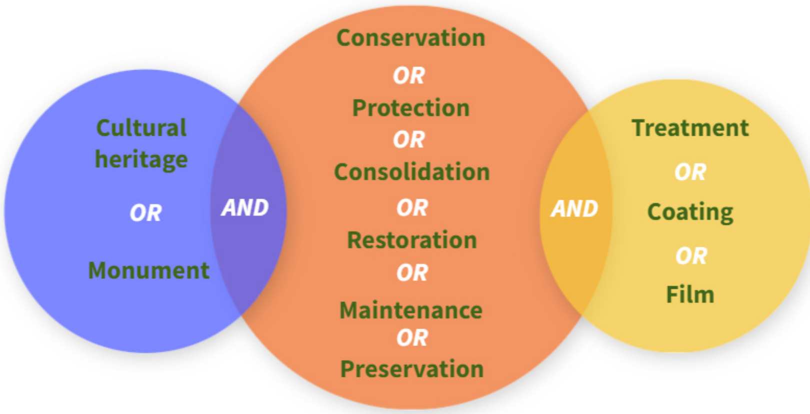

Figure 1. Search terms for data collection.

2.2. Bibliometric Analysis

The determination of bibliometric parameters allows for the quantitative analysis of scientific literature and the assessment of academic productivity [18]. There are different types of bibliometric indicators that can be classified as: quantity indicators, which measure the productivity of journals or authors; quality indicators, which measure the relevance and influence of authors, publications, and journals; and structural indicators, which measure interconnections and relationships between publications, authors, and areas of research [21]. It is recommended that a combination of multiple indicators is used to cover various aspects of scientific output simultaneously [22]. However, using certain bibliometric indicators, such as citation counts or the H-index, may have limitations, including field dependency, self-citation, language and geographic biases, etc. [22,23].

According to Rogers et al. (2020) [24], it is recommended to conduct bibliometric analysis only when there is a minimum of 200 documents to be reviewed. They found that smaller sample sizes (<200) result in high variance in the average category-normalized citation impacts of bibliometric analyses, making this method not advisable.

In this study, the database was composed of 1501 documents. Indicators such as the number of citations and the h-index of the authors were obtained directly from Scopus. In addition, VOSviewer (University of Leiden, Netherlands, version 1.6.19) [25] was used to conduct the correlations and visualization among countries/regions, topics, and citations. VOSviewer allows for the construction of networks of scientific publications, scientific journals, researchers, research organizations, countries, keywords, or terms and display bibliometric relationships between a variety of variables such as co-authorship, cooccurrence, citation, bibliographic coupling, or co-citation links [26]. VOSviewer was selected because it is a freely available software used in many other articles of bibliometric analysis [27–29]. In addition, it is capable of loading and exporting information from different sources, and it has a great visualization.

2.3. Latent Dirichlet Allocation (LDA) Methodology

Latent Dirichlet Allocation (LDA) methodology was also employed. LDA is a popular machine learning technique used in natural language processing (NLP) to uncover underlying topics within a collection of documents. LDA assumes that each document is a mixture of various topics and that each word in the document is generated from one of these topics. The goal of LDA is to infer the topic distribution of each document and the word distribution of each topic. This unsupervised learning algorithm operates by iteratively assigning words to topics and updating the topic distributions based on statistical inference. By analyzing the co-occurrence patterns of words across multiple documents, LDA can identify distinct topics and their prevalence within the corpus. LDA provides a probabilistic framework to explore the hidden thematic structure of a document collection, enabling researchers to gain insights into the main themes and uncover the relationships between topics.

In the context of bibliometrics, LDA offers valuable insights and tools for analyzing large volumes of scholarly publications. By applying LDA to a collection of scientific articles, researchers can identify the underlying topics that emerge from the corpus. This topic modeling approach can assist in various bibliometric analyses, such as identifying research trends, mapping the intellectual structure of a field, and uncovering interdisciplinary connections. LDA can also aid in document clustering and categorization, allowing researchers to group related articles based on their thematic similarity. Furthermore, LDA can help in measuring the influence of individual articles or authors within a topic, facilitating the identification of key contributors or influential works. By leveraging LDA, bibliometric studies can gain a deeper understanding of the knowledge landscape, discover emerging areas of research, and make informed decisions based on the extracted topics and their associated metrics.

Numerous researchers have utilized the LDA technique for thematic organization within article databases. Gupta et al. (2017) [30] employed LDA for trend analysis and prediction across a dataset of 3269 articles from the Journal of Applied Intelligence, spanning three decades. Kim et al. (2019) [31] crafted a classification system that merges the TF-IDF and LDA methods, effectively grouping research papers by subject similarity. George et al. (2023) [32] further expanded the utility of LDA by combining it with clustering and BERT, presenting a hybrid model that enhances topic detection and improves the performance of topic modeling across extensive text collections. The alternatives to LDA, like TF-IDF, PCA, and LSA, either focus on term frequency or use linear methods, which are less effective at uncovering complex, hidden thematic structures. LDA, as a generative probabilistic model, provides a deeper and more nuanced analysis by revealing the probabilistic distribution of topics within documents. This makes LDA particularly robust for handling large text datasets and identifying underlying trends, offering a more comprehensive understanding of the literature. These instances underscore the adaptability of LDA in bibliometric studies, facilitating everything from forecasting research trends to refining the precision of topic models through the integration of sophisticated computational techniques.

In this study, LDA methodology has been employed, fixing a number of 8 topics as the target for topic identification. We chose to use eight topics for our LDA model to balance sufficient granularity with the necessary generalization. To determine this, we simulated models with numbers of topics ranging from 1 to 10. Through this process, we observed that eight topics provided the best compromise, maintaining both topic coherence and interpretability. Models with fewer topics lacked detail, while those with more topics resulted in less generalizable themes.

3. Results and Discussion

3.1. Annual Publications and Document Type

Observing the annual frequency of publications is the most fundamental way to understand the performance in a specific field. Figure 2a illustrates the annual distribution of the number of publications. The number of publications in the field increased exponentially in the period of study (1990–2023). The first literature document was published in 1990. However, in the first few years (1990–2000 inclusive), the number of articles did not exceed five publications per year, and the data suggest that greater attention was given after 2010. The maximum number of publications was reached in 2022, with a total of 150 documents. Regarding the types of documents (Figure 2b), most of the publications were articles and conference papers.

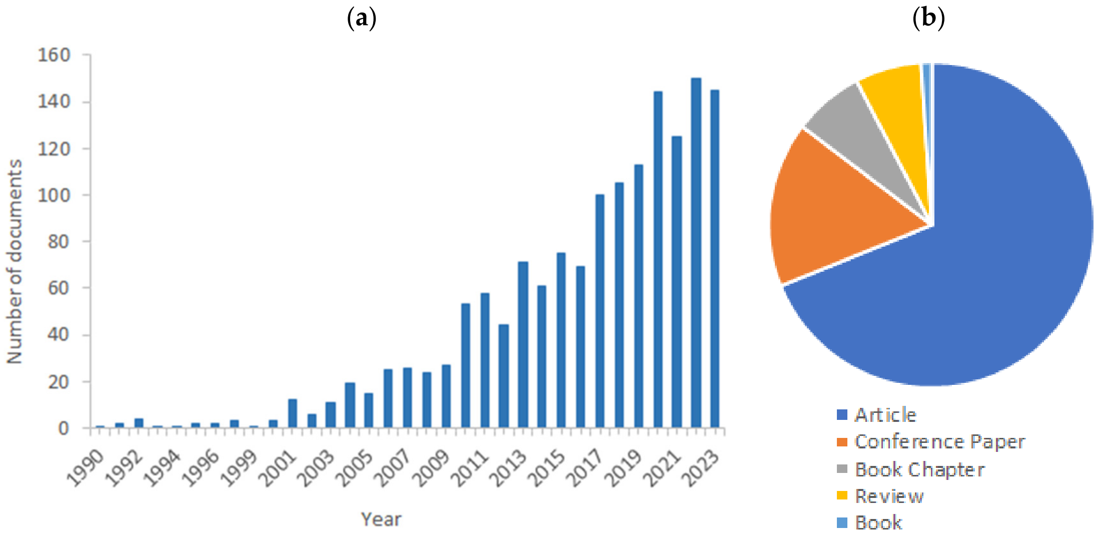

Figure 2. Research documents on cultural heritage protection: (**a**) number of publications per year; (**b**) document classification.

The exponential increase in the number of publications can be attributed to various underlying factors. Many regions, mainly in Europe, have concentrated efforts on preserving their cultural heritage as a way to maintain their identity and promote tourism. Additionally, Europe, with its rich cultural heritage, has been actively engaged in preserving its historical sites, resulting in a surge of research and publications in this field. The increased funding for innovation has also significantly boosted research efforts in cultural heritage conservation. Lastly, the rise in tourism over the past few years has highlighted the importance of maintaining and protecting monuments and heritage sites, further driving research and innovations in conservation techniques.

3.2. Countries

The 1501 articles retrieved to compose the study database were obtained from more than 90 contributing countries. The geographical distribution of publications is shown in Figure 3, and the number of documents per country is represented in Figure 4.

Europe is home to a substantial number of UNESCO World Heritage Sites, with Italy, Spain, and France among the top countries with the most sites. This abundance of cultural heritage needs extensive research and conservation efforts, driving a high volume of publications from these regions. Moreover, Europe counts on a robust funding landscape, enabling extensive research activities and the publication of numerous studies. In particular, programs such as Horizon 2020 give access to significant funding for cultural heritage projects.

Italy is home to the largest number of UNESCO heritage sites and hosts numerous specialized institutions and universities which are at the forefront of conservation research. For that, Italy is the most prolific country in terms of publications in the field of conservation of cultural heritage, followed by Spain. Both together constitute 43% of the total publications in the field. Together with China and United States, they are far from the next countries in the list, which have less than 100 documents. It is worth it to mention that in other scientific fields, China and the United States tend to be the most prolific countries, but this is not the case in the field of cultural heritage.

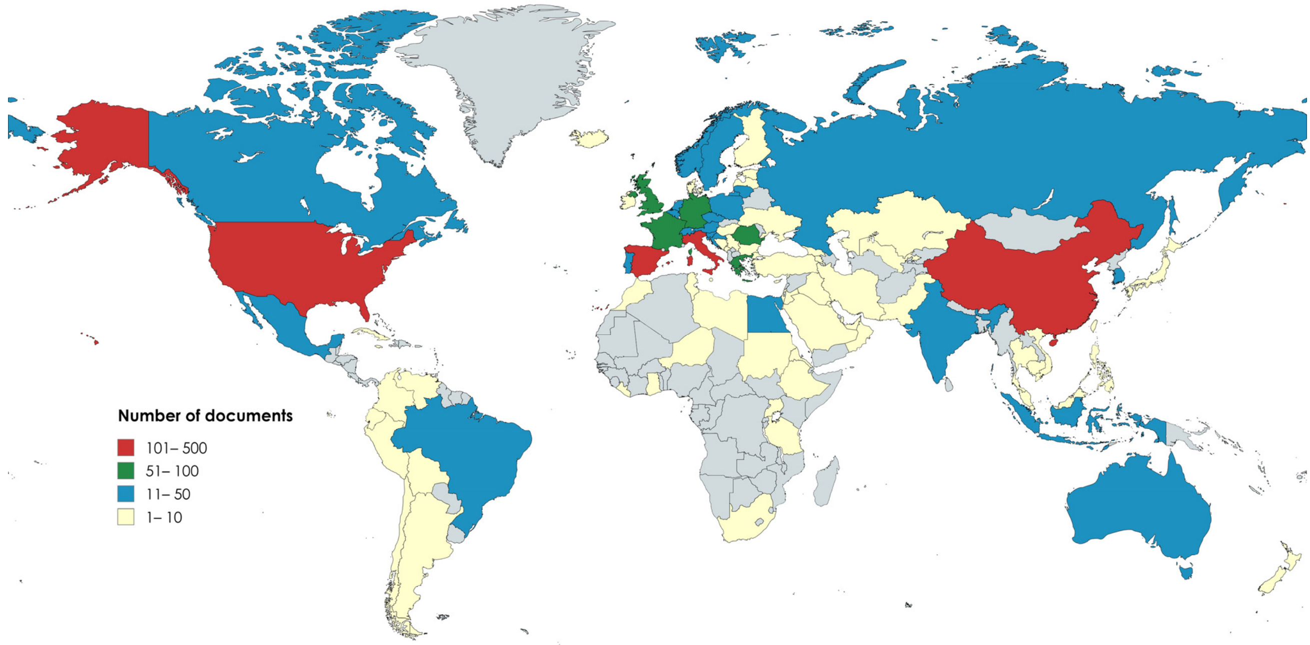

Figure 3. Geographical distribution of publications (created with Mapchart [33]).

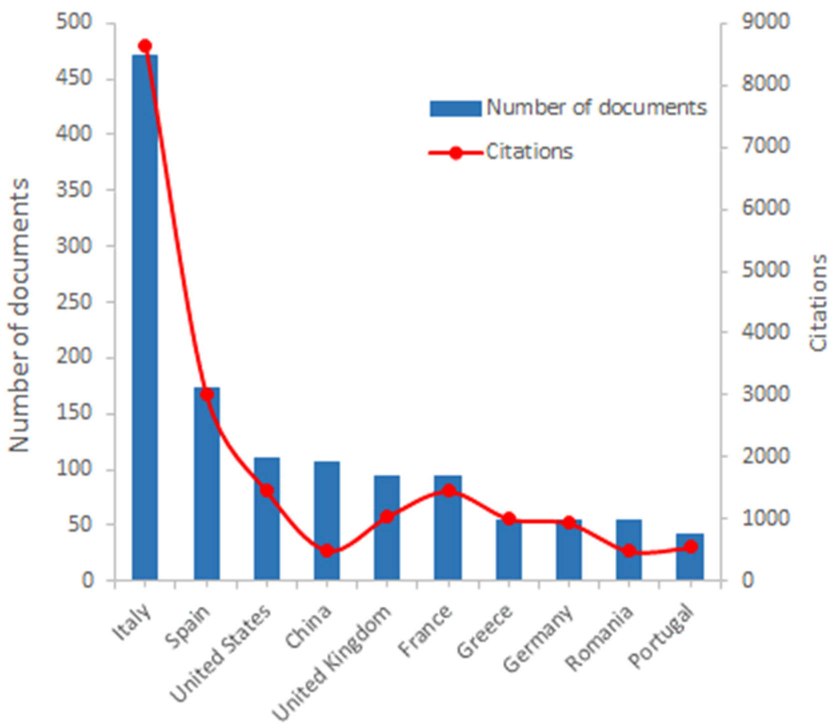

Figure 4. Top 10 countries by number of publications.

However, the number of publications is not relevant if articles are not cited. Thus, the total number of citations, together with the number of documents, is also evaluated in Figure 4. Italy and Spain, again, have the highest number of citations. It is also worth mentioning that China, a country with a high number of publications, has a low rate of citations compared to the rest of the top 10 countries.

Moreover, the co-authorship between countries is shown in Figure 5. Co-authorship analysis can aid in identifying the trends and nature of research collaborations, as well as uncovering the existence of certain research groups in terms of collaborations [34]. Only countries with a minimum number of eight documents are included in the map, and the co-authorship analysis revealed the existence of eight clusters.

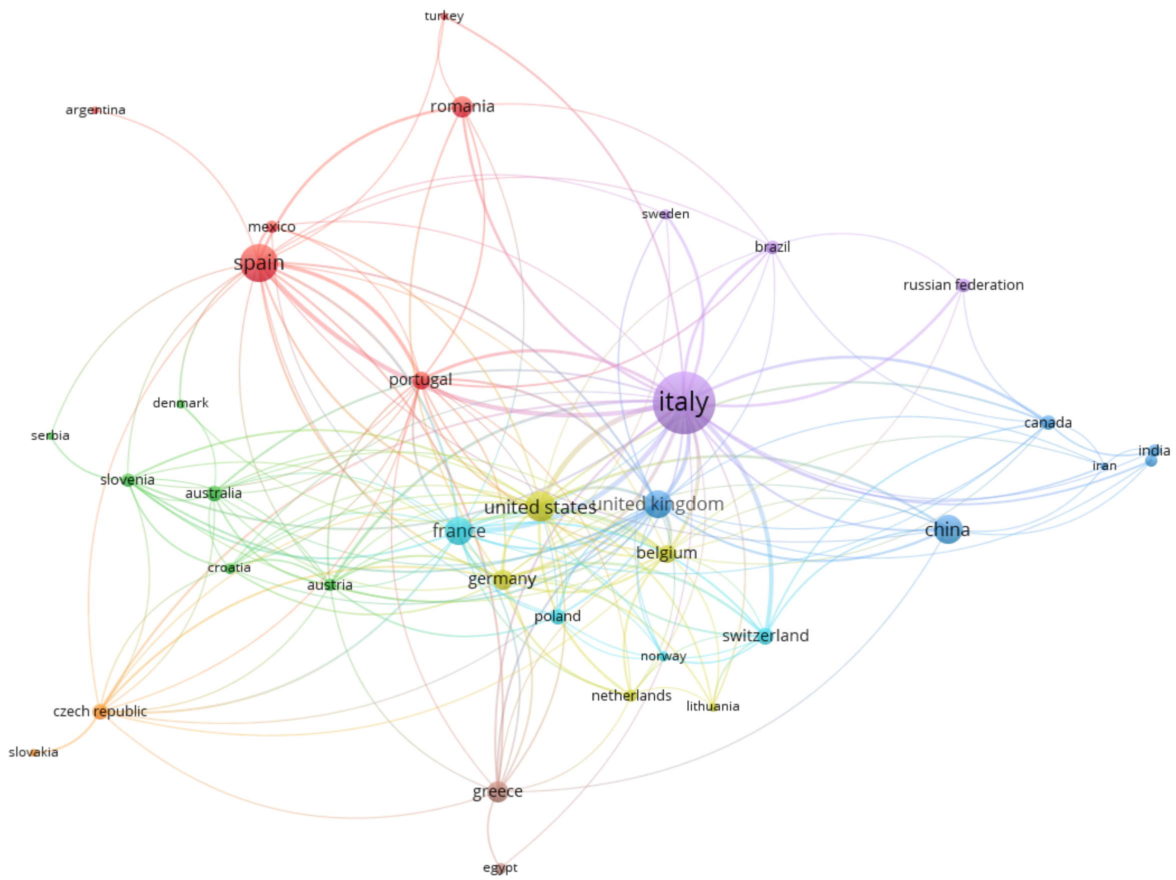

Figure 5. Co-authorship between countries.

Italy was found to have the strongest research collaboration, with the highest total link strength (TLS = 170). In terms of collaboration, Italy is followed by the United States (TLS = 72), France (TLS = 69), the United Kingdom (TLS = 68) and Spain (TLS = 64). This means that the United States, France, and the United Kingdom have similar numbers of collaborations, although the number of published documents is considerably inferior to that of Spain. In the case of China, although it is the fourth country in terms of number of publications, it only has a TLS of 20.

3.3. Most Cited Articles

The most cited publications from the document collection are listed in Table 1. The number of citations that a publication receives serves to measure its quality and influence [18].

With 288 citations, the book titled "Microclimate for cultural heritage" [35] is the most cited document of the collection. It is a handbook targeted at conservators and specialists in various fields, covering non-destructive diagnostics and practical strategies for mitigating atmospheric damage to works of art, integrating theoretical knowledge with extensive research and field experience. This handbook has been widely cited because it addresses the fundamental issue of environmental impact on cultural heritage, which is fundamental to understand before any intervention.

The rest of the publications consist of scientific articles or reviews, which can be classified into two main groups: those focused on materials and those related to characterization techniques applied in the field of cultural heritage.

Articles included in the first group (materials) have led to significant citations due to the novelty and effectiveness of the materials proposed. These articles can be divided at the same time according to the type of treatment intervention they are involved in:

- Cleaning: The use of gels has been widely extended in the field of cultural heritage restoration as they reduce the permeation of solvents used to clean surfaces. However, the utilization of gels presents some difficulties in their removal and may leave residues on the surface of the work of art after the application. In this sense, Carretti et al., 2010 [36] discussed a possible solution to the removal problem of gels in artwork conservation through three types of innovative responsive gels: rheoreversible, magnetic, and "peelable" gels. These gels can be easily and rapidly removed via a response to a "chemical switch" (rheoreversible gels) or an external magnet (gels with embedded magnetic nanoparticles). The novelty and practical applicability of these gels have acquired significant attention in the field as they offer simple solutions to common conservation problems.
- Consolidation: As reported by Giorgi et al. [37] and many other researchers, the consolidation of paintings, stone, paper, and wood frequently involve the use of calcium hydroxide dispersions, ensuring complete compatibility with the original materials. This has been also the focus of the investigation of Dei et Salvadori [38], where limestones and painted surfaces affected by different kinds of decay were consolidated by using nanosized particles of calcium hydroxide dispersed in an alcoholic medium. On the other hand, Bertolino et al. [39] also reviewed works where composites containing halloysite nanotubes were used for the consolidation of paper and wooden artifacts.
- Protection: La Russa et al. [40] developed an organic coating to obtain biocidal and hydrophobic functionalities. The coating was composed of an aqueous dispersion containing an acrylic polymer and anatase TiO_2 nanoparticles and was applied to marble and limestone specimens. The results showed great growth inhibition efficiency and good water repellence after the treatments on both lithotypes. Also, Manoudis et al. [41] used common nanoparticles (SiO_2, Al_2O_3, SnO_2, and TiO_2) and siloxane products to obtain superhydrophobicity functionality on stone surfaces. The results showed that nanoparticles induced superhydrophobicity, but affected the aesthetic appearance of the studied stones.

The other three documents of the top 10 most cited articles are related to characterization techniques applied in the field of cultural heritage. The application of diverse characterization techniques is of paramount significance in assessing the condition of cultural heritage and evaluating the efficacy of conservation interventions to ensure the preservation and longevity of cultural heritage. Employing a range of methodologies such as spectroscopic analysis, imaging techniques, and material testing enables a comprehensive understanding of, among others, the composition, deterioration mechanisms, and structural integrity of cultural assets. These techniques facilitate the identification of specific materials, the detection of hidden features or damages, and the monitoring of changes over time. Moreover, through the integration of multiple characterization methods, conservation efforts are enriched with accurate data, fostering informed decision making and enhancing the safeguarding of our cultural legacy. In this context, Cano et al. [42] reviewed the utilization of Electrochemical Impedance Spectroscopy (EIS) for the study of protective coatings for metallic cultural heritage. They concluded that this technique, initially used for metallic coatings, has gained popularity for the evaluation of metallic cultural heritage, proving to be a valuable tool for conservators in selecting appropriate coatings and evaluating protective characteristics. Based on the number of citations, EIS has proven to be a valuable tool for conservators, and this review provides a thorough understanding of and guidance on its application. On the other hand, Chércoles et al. [9] reported the use of ATR-FTIR spectroscopy to analyze polymeric materials used for cultural heritage. In the same line, Prati et al. [43] described the advances in FTIR spectroscopy and microscopy for the characterization of artistic materials. As Fourier Transform Infrared (FTIR) spectroscopy is the most frequently used technique to identify not only polymers, but also additives and fillers, its use has been widely reported in the field of cultural heritage [44,45].

Table 1. Top 10 cited publications.

#	Title	Authors	Year	Source	Type	Cites	Ref.
1	*Microclimate for cultural heritage*	Camuffo	1998	Microclimate for cultural heritage	Book	288	[35]
2	*New frontiers in materials science for art conservation: Responsive gels and beyond*	Carretti et al.	2010	Accounts of Chemical Research	Article	202	[36]
3	*Use of EIS for the evaluation of the protective properties of coatings for metallic cultural heritage: A review*	Cano et al.	2010	Journal of Solid State Electrochemistry	Review	201	[42]
4	*Analytical characterization of polymers used in conservation and restoration by ATR-FTIR spectroscopy*	Chércoles et al.	2009	Analytical and Bioanalytical Chemistry	Article	198	[9]
5	*Multifunctional TiO_2 coatings for Cultural Heritage*	La Russa et al.	2012	Progress in organic coatings	Article	190	[40]
6	*Polysaccharides/Halloysite nanotubes for smart bionanocomposite materials*	Bertolino et al.	2020	Carbohydrate Polymers	Review	170	[39]
7	*New Methodologies for the conservation of cultural heritage: Micellar solutions, microemulsions, and hydroxide nanoparticles*	Giorgi et al.	2010	Accounts of Chemical Research	Article	156	[37]
8	*Nanotechnology in cultural heritage conservation: nanometric slaked lime saves architectonic and artistic surfaces from decay*	Dei et Salvadori	2006	Journal of Cultural Heritage	Article	139	[38]
9	*New advances in the application of FTIR microscopy and spectroscopy for the characterization of artistic materials*	Prati et al.	2010	Accounts of Chemical Research	Article	138	[43]
10	*Superhydrophobic films for the protection of outdoor cultural heritage assets*	Manoudis et al.	2009	Applied Physics A: Materials Science and Processing	Article	136	[41]

3.4. Journals and Authors

The 1501 publications studied were published in 680 different sources. Information about the journals in which articles are most frequently published is presented in Table 2. The number of documents and citations and and JCR impact index are depicted for the top 10 journals. A total of 291 publications were published in the 10 most productive journals, representing 20% of all papers.

Table 2. Top 10 journals with higher numbers of articles.

Journal	Documents	Citations	JCR Impact Factor (2022)
Journal of Cultural Heritage	80	1631	3.1
Studies in Conservation	37	159	0.8
Coatings	34	337	3.4
Progress in Organic Coatings	28	867	6.6
Heritage Science	22	402	2.5
Heritage	19	71	1.7
Radiation Physics and Chemistry	19	250	2.9
Applied Sciences (Switzerland)	18	201	2.7
Applied Physics A: Materials Science and Processing	17	592	2.7
International Biodeterioration and Biodegradation	17	686	4.8

As the leading journal, *Journal of Cultural Heritage* published 80 articles (5%), followed by *Studies in Conservation* and *Coatings*. The JCR impact factor measures the quality of the journal by taking into account indexed citations [18]. Most of the top 10 journal have a JCR impact factor > 1, and the journal with the highest impact factor is *Progress in Organic Coatings.*

It is worth noting that the *Journal of Cultural Heritage*, the journal with the highest number of articles, has an editorial board that is mainly Italian, again demonstrating Italy's dominance in this field.

According to the data, most authors have conducted independent academic research with weak cooperative relationships, except those belonging to the same institution who have frequently been co-authors. In Table 3, the most prolific authors are listed. Nine out of the top ten authors work in Italian academic institutions, confirming once again that Italy is the most prominent country in the field of cultural heritage conservation.

Table 3. Top 10 authors with higher numbers of publications in the field.

	Author	Country	Affiliation	Documents	Citations	H Index
1	Baglioni, P.	Italy	Università degli Studi di Firenze	29	1022	64
2	La Russa, M.F.	Italy	Università della Calabria	18	575	32
3	Grassini, S.	Italy	Politecnico di Torino	15	115	24
4	Karapanagiotis, I.	Greece	Aristotle University of Thessaloniki	15	653	33
5	Sassoni, E.	Italy	Alma Mater Studiorum Università di Bologna	15	438	27
6	Chelazzi, D.	Italy	Università degli Studi di Firenze	14	261	34
7	Giorgi, R.	Italy	Università degli Studi di Firenze	14	570	35
8	Angelini, E.	Italy	Politecnico di Torino	12	138	35
9	Franzoni, E.	Italy	Alma Mater Studiorum Università di Bologna	12	396	33
10	Ruffolo, S.A.	Italy	Università della Calabria	12	569	30

3.5. Keywords

Firstly, Latent Dirichlet Allocation (LDA) methodology was employed to identify key research themes and trends by clustering the documents based on shared topics. A fixed number of eight topics was chosen as the target for topic identification, as explained in Section 2.3.

To automatically assign names to the resulting groups, the OpenAI API was utilized. The prompt provided to the API was: "Define the following groups obtained through LDA by assigning a name to each topic". As the GPT4 model provides different responses each time an input is entered, the assignment name process was iterated five times, and the authors selected the most appropriate topic name for each group. The number of articles where the topic score exceeded 0.1 varied across the groups, ranging from nearly a thousand to a few articles, reflecting the prevalence and importance of these topics in scientific collection.

Table 4 presents eight distinct groups, each associated with a set of words derived through LDA methodology from the database of scientific articles provided. For instance, Group 0 includes the largest number of articles because the keywords that define the topic are those used in the initial search. Group 1, labeled as "Stone Conservation and Surface Treatment", emphasizes the preservation and treatment of stone, which is the oldest and most common material used in built cultural heritage, mainly limestones, marbles, sandstones, and granites [46]. The presence of high humidity and microorganism colonization reduces stone's mechanical properties [47]. However, preservation of stone in cultural heritage is a more effective method of intervention than substitution of the altered stones. Group 2, termed "Urban Heritage and Cultural Preservation", groups together documents related the preservation of urban heritage, as most of the cultural heritage assets are located in cities. Groups 3 and 5 include documents that cover the most relevant degradation mechanisms in the field of cultural heritage: corrosion and biodeterioration, respectively. Group 4, named "Digital Imaging and Modeling Techniques", gathers papers related to characterization techniques mainly based on digital imaging. Diagnostic investigations are vital in cultural heritage studies, and in this context, the use of innovative and non-destructive techniques such as imaging and the development of transportable and versatile devices allows for the retrieval of relevant hidden information [48]. Group 6, labeled as "Eco-Environmental Studies", gathers research on the intersection of ecology and cultural heritage, examining how ecosystems, soil, and local knowledge contribute to the conservation of cultural assets. With 21 articles, this theme explores the role of natural elements and environmental services in preserving cultural landscapes and materials, reflecting a growing interest in sustainable conservation practices. Lastly, Group 7, "Historical Artifacts and Materials", with the smallest cluster of six articles, focuses on the specific materials and techniques associated with historical artifacts, including unique methods of preservation and analysis of items from specific cultural or historical contexts, such as temples and ancient metallurgy.

Furthermore, an analysis of these highlighted topics over time was conducted and is represented in Figure 6. It can be observed that most articles were produced in Topic Groups 0, 1, and 2 in the last six years.

Together with this analysis, keyword co-occurrence maps are useful for the identification of hot topics. In these maps, each word is depicted as a node, while each co-occurrence of a pair of words is represented as a link [49]. The size of the node indicates the importance of the term, and the frequency of occurrences of a word pair across various articles determines the strength of the connection linking them.

Table 4. Categorization of topics in cultural heritage conservation using LDA.

Group Number	Top Ten Words That Define Each Topic	Assigned Topic Name by GPT4 Model	Number of Articles Where Topic Score Is > 0.1
0	conservation, heritage, cultural, material, treatment, paper, study, method, used, restoration	Cultural Conservation and Restoration	965
1	stone, coating, surface, water, treatment, heritage, material, cultural, based, property	Stone Conservation and Surface Treatment	625
2	heritage, cultural, film, preservation, building, research, value, urban, treatment, conservation	Urban Heritage and Cultural Preservation	439
3	corrosion, wood, silver, coating, electrochemical, iron, sample, treatment, spectroscopy, metallic	Corrosion Protection and Material Conservation	223
4	image, model, digital, data, painting, lacquer, imaging, information, virtual, technique	Digital Imaging and Modelling Techniques	104
5	fungal, fungi, bacteria, bacterial, strain, film, specie, cinematographic, gelatin, aspergillus	Microbial Biodeterioration and Conservation	26
6	plant, ecosystem, soil, service, wetland, medicine, wastewater, masseur, knowledge, local	Eco-Environmental Studies	21
7	temple, hong, coppice, bronze, worn, coat, sucrose, tabia, eicp, phou	Historical Artifacts and Materials	6

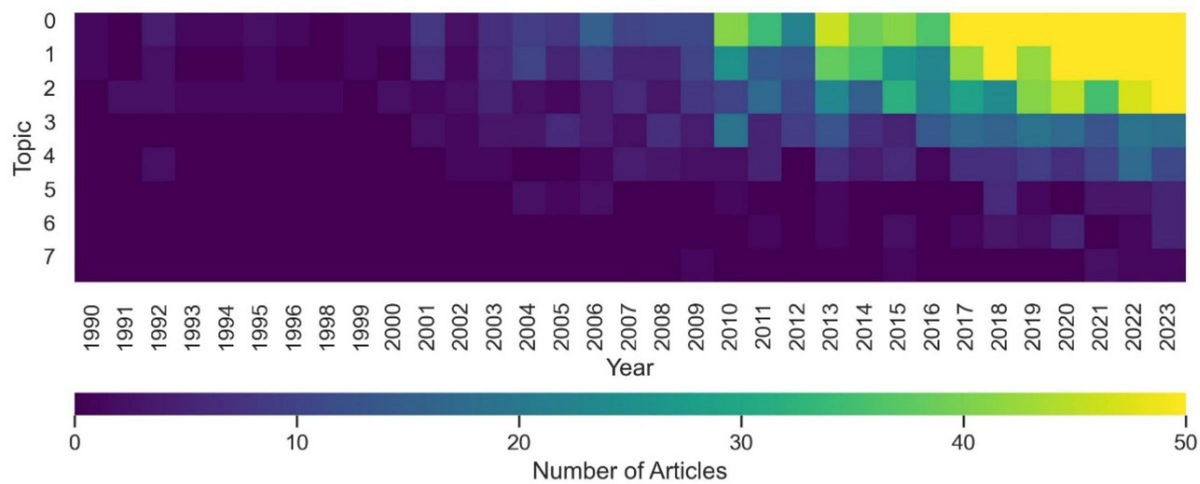

Figure 6. Heatmap with the evolution of the topics determined by LDA method (included in Table 4).

Figure 7 provides a visual representation of the network of keyword co-occurrence obtained with VOSviewer with the document collection. First, a keyword co-occurrence map including all the keywords used in the documents contained in the collection was created. However, the output revealed that, as expected, the most important words were those used in the initial search in Scopus. For this reason, the words "cultural heritage", "monument", "conservation", "protection", "consolidation", "restoration", "maintenance", "preservation", "treatment", "coating", and "film" were excluded in order to identify significant terms not included in the search. The minimum number of occurrences of a keyword established was 25, and a new map was generated (Figure 7).

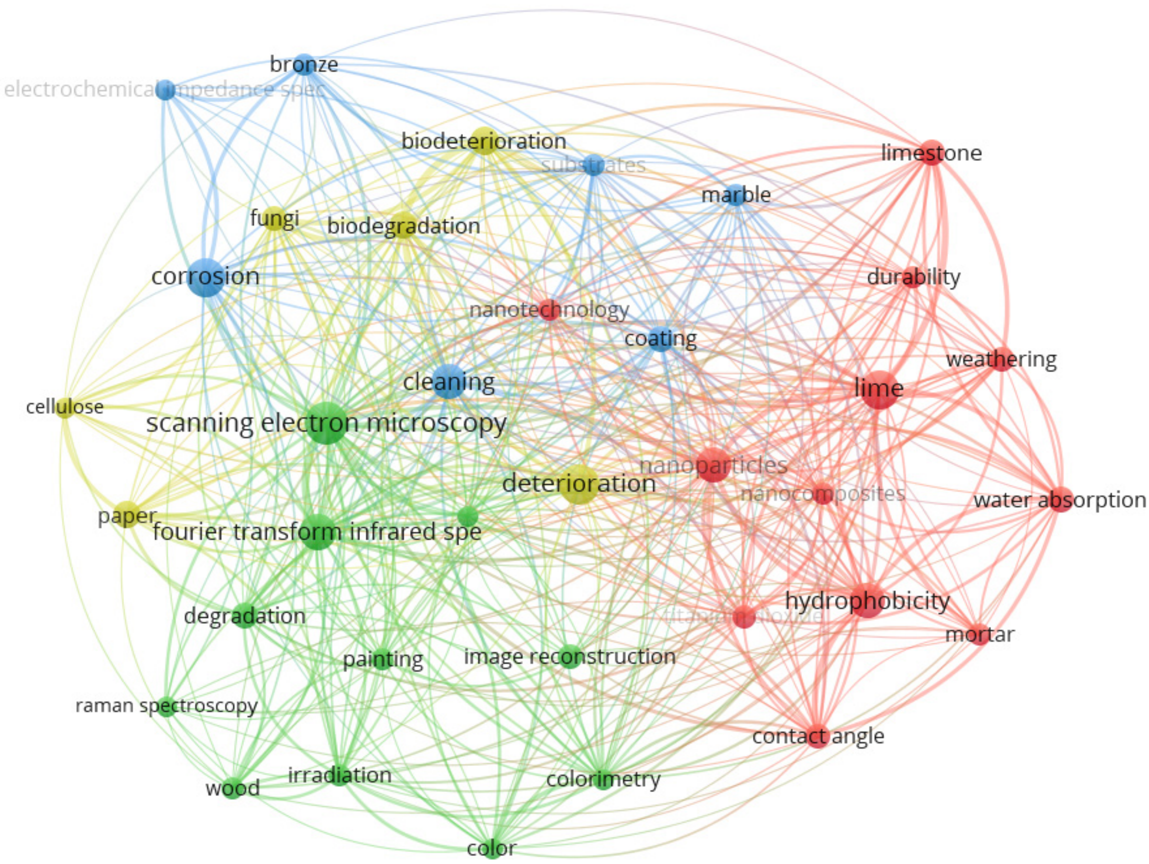

Figure 7. Keyword co-occurrence map (without keywords of search).

As can be seen in the keyword co-occurrence map, the majority of the highlighted words are related to types of substrates (lime, marble. . .), treatment materials (nanoparticles, nanocomposites. . .), analytical techniques (F-TIR, SEM. . .), and functionalities (deterioration, cleaning, biodegradation. . .).

Based on these four major groups, a refined analysis of word frequency was conducted. For this purpose, a list of terms and their synonyms for each group was compiled. Then, a Python script was developed to search through the document database, counting "1" each time a term or its synonym appeared in the Title, Keywords, or Abstract Sections. This method enabled the counting of articles that mentioned any of the terms or their synonyms, as defined for the four groups. The results of this analysis are represented in Figure 8.

Regarding the substrates (Figure 8a), most of the studies were related to metal, paper, and stone. Metals such as bronze, iron, gold, and silver have been extensively used throughout history due to their high mechanical resistance and durability in producing tools such as weapons, jewelry, and other structures. However, metals can present long-term corrosion problems, and there are many research works related to the development of different corrosion protection treatments. Paper, in second place, though more fragile than other materials, revolutionized the recording and dissemination of information, making it an indispensable material in written heritage. Manuscripts, books, maps, and documents are primary sources of historical knowledge. Stone is one of the oldest and most durable materials used in cultural heritage. Monuments, sculptures, temples, and historical buildings from various civilizations are made from different types of stone, such as marble, granite, limestone, and sandstone. Its durability has made stone a fundamental material in constructing significant structures. However, it is affected by weathering and there are plenty of research works on improving its resistance without affecting the aesthetic appearance, assuring good permeability for water vapor, and decreasing the amount of water absorbed by capillarity [41].

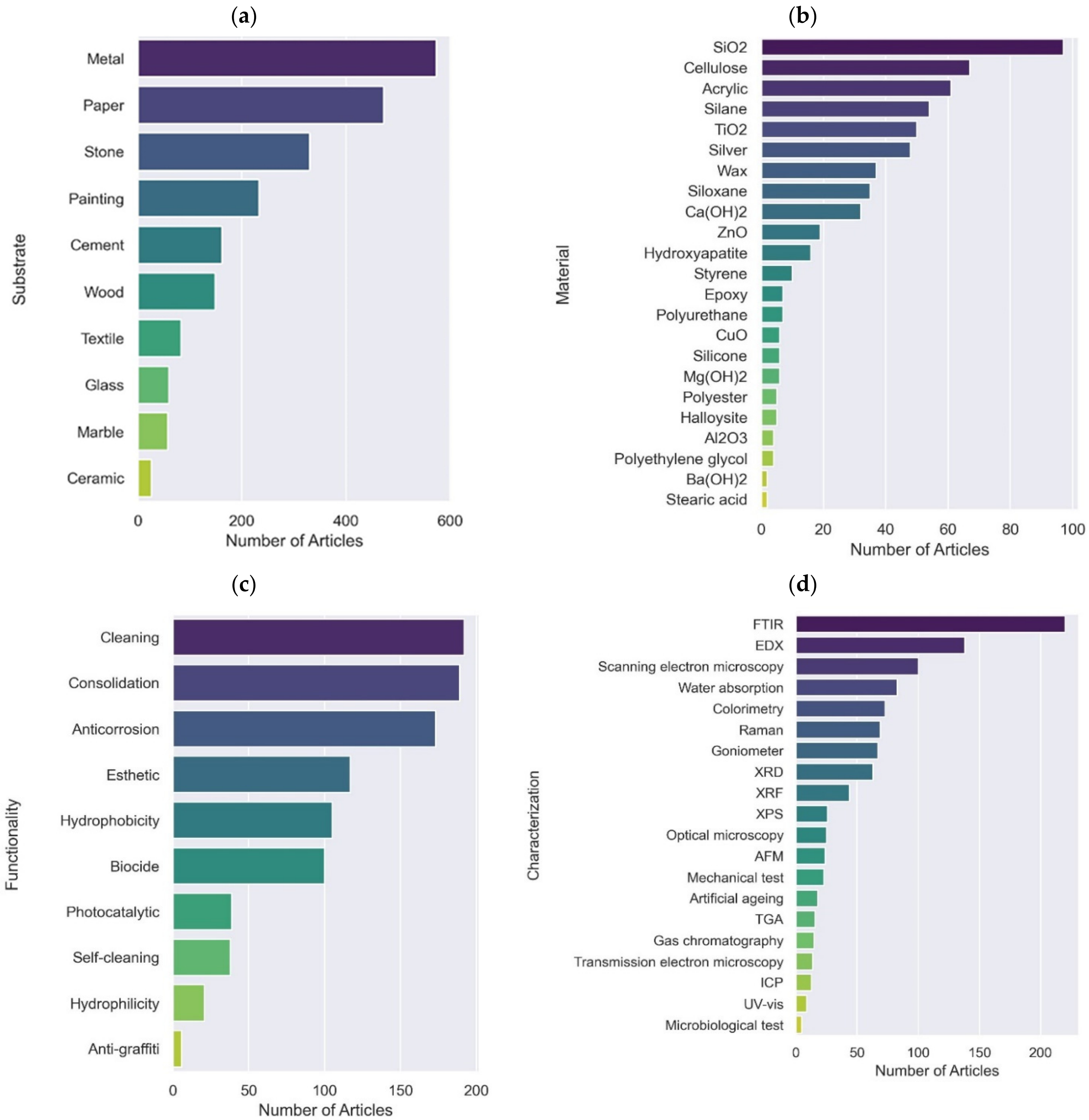

Figure 8. Frequency of keywords in research documents on cultural heritage protection classified by (**a**) substrate; (**b**) materials' treatment; (**c**) functionality and (**d**) characterization techniques.

On the other hand, the top materials related to protection treatments are displayed in Figure 8b. The five most common materials that resulted from the analysis were SiO_2, cellulose, acrylic, silane, and TiO_2. The use of SiO_2 and TiO_2, more recently at the nanoscale, provides effective protection by enhancing their resistance to environmental degradation and biological growth. The high frequency of cellulose may likely be due to the fact that, as previously mentioned, paper is the second most common substrate, and this frequency analysis cannot make that distinction. However, cellulose has also been widely used for conservation, lately at the nanoscale. Moreover, the most commonly used materials as matrices have been based on organic resins, including acrylic ones [50]. Nevertheless, protective formulations must not only offer protection, but also meet a series of aesthetic requirements, and in this sense, such types of resins present some drawbacks. Over time, they can undergo physicochemical changes, leading to yellowing and embrittlement of the film, which complicates the removal process and potentially harms the artwork [37]. In this case, it is also worth mentioning that acrylic resins are used in modern painting. That is, the high frequency does not directly imply that they are part of the protection treatment, but rather that they may have been employed in the painting base itself. Lastly, the high frequency of silanes may be due to the fact that these compounds are widely used to achieve hydrophobicity and superhydrophobicity functionalities.

The keyword frequency analysis related to the functionalities to be achieved (Figure 8c) revealed that the most commonly sought properties in cultural heritage protection treatments are cleaning, consolidation, and corrosion resistance. Functional treatments can be tailored to the specific needs of different materials. Effective cleaning methods are crucial because they remove dirt, pollutants, and biological growth that can cause damage and aesthetic changes. Consolidation treatments reinforce the structural integrity of these items. Preventing further decay and extending their lifespan and corrosion resistance is important mainly for metal structures, which are particularly susceptible to degradation from environmental exposure.

Finally, the frequency of appearance of characterization techniques is represented in Figure 8d. The usefulness of listing these techniques can aid future research by identifying the most used methods in the field and enabling comparisons of results with other studies. The most used technique for characterizing cultural heritage is FTIR, as has been discussed throughout the present study. It is followed by EDX, which indicates that the predominant type of characterization applied to cultural heritage assets is compositional analysis. Subsequently, there are techniques for measuring other types of characteristics, such as water absorption (permeability/porosity), color, contact angle, etc.

The identified hotspots represent the most active areas of research and development within the field of cultural heritage protection and conservation. These areas reflect the approaches and techniques currently receiving the most attention and resources. This is valuable as it indicates where the greatest advancements are being made and where the most promising innovations are found. However, it is essential to recognize that cultural heritage protection is a multifaceted discipline facing a variety of challenges. Some of these challenges may not be prominently represented in the identified hotspots, but are equally important.

3.6. Research Trends

3.6.1. Non-Invasive Analytical Techniques

The current practices for the conservation and protection of cultural heritage must be preceded by exhaustive analysis to determine the deterioration level. Moreover, decision making to select the type of intervention and the conservation materials should be based on precise diagnostic results.

In this context, advancements in physical and chemical characterization techniques have been successfully implemented in the field over recent decades and have enabled researchers to implement ultrasensitive detection [51]. In particular, non-invasive and portable analytical techniques have emerged as indispensable tools, offering in situ application without destructive sampling [52,53] (e.g., X-ray fluorescence, Raman spectroscopy…). Moreover, the emergence of hybrid systems combining simultaneously various analytical methods has facilitated a more uniform and time-efficient approach to acquiring data [54,55]. However, the wide variety of analytical techniques requires the application of chemometric methods to extract meaningful information from complex physicochemical datasets [55,56].

As non-invasive and non-destructive techniques, neutron-based [57] and synchrotron radiation [58,59] technologies are very promising for quantitative investigation. Synchrotron and neutron scientific facilities are advanced resources with high potential for material research [58]. Over recent years, there has been increasing demand for access to these type of facilities as they provide better characterization with high spatial resolution and accurate compositional information, and, thus, deeper understanding in aging studies [60].

Also, the interest in the use of monitoring sensors has notably increased, allowing for early detection of risks [61,62]. Modern sensors, designed for preserving cultural heritage, can combine physicochemical measurements with advanced data processing algorithms [63,64]. Due to the diversity of materials' characteristics, there is a need for the continuous development of new measurement methods and their integration in sensors. The combination of sensors and artificial intelligence (AI) techniques has opened new opportunities and challenges in the analysis and protection of cultural heritage, allowing us to advance one step further in the prediction of damages and risks [64–66].

Precisely, the use of AI-based prevention methods can revolutionize the conservation efforts of cultural heritage worldwide. Firstly, AI-powered systems can analyze vast amounts of data, and this broad analysis enables precise monitoring, predictive maintenance, and proactive preservation strategies for historical buildings, monuments, and artifacts [67]. Moreover, AI facilitates comprehensive documentation and digital restoration of cultural artifacts [68]. High-resolution imaging combined with AI algorithms can reconstruct damaged or fragmented artifacts digitally, preserving their original form for future generations. Additionally, AI-driven virtual reality (VR) and augmented reality (AR) applications offer immersive experiences, allowing the public to explore and interact with cultural heritage sites and artifacts virtually regardless of geographical constraints, democratizing access to cultural knowledge and heritage [69,70].

3.6.2. Nanotechnology

As previously stated, current trends in treatments and coatings for cultural heritage focus on protection (against corrosion, colonization, friction, wear, etc.), the addition of functionalities (such as hydrophobicity and self-repair), and even the development of smart coatings (sensors, dynamic adhesion, controllable hydrophobicity). For technical and economic reasons, the search for innovative materials with maximized performance by fully utilizing their inherent properties has gained increasing interest. Recent developments have demonstrated that conservation efforts for cultural heritage can be effectively and satisfactorily carried out through the use of nanomaterials [14,17], which opens up a new era of possibilities for producing materials with enhanced characteristics and functionalities. Nanomaterials (in the range of 1–100 nm) exhibit a high specific surface area, leading to increased reactivity with their environment and the ability to penetrate substrates due to their reduced size. This still makes them excellent candidates in future's strategies for consolidating and protecting cultural heritage [13].

Among the most common nanoparticles utilized, silica and its derivatives stand out. The formulations of SiO_2 nanoparticles can vary based on the specific requirements of the substrate and the conservation objectives. For instance, colloidal silica-based consolidants are commonly used due to their ability to penetrate porous materials effectively. These consolidants form durable bonds with the substrate, enhancing its mechanical strength and resistance to weathering without altering its appearance. SiO_2-based materials are also frequently formulated into coatings [71]. Functionalized SiO_2 nanoparticles can impart functionalities such as hydrophobicity [71,72], self-cleaning [73], and antimicrobial activity [60], further enhancing the durability and longevity of treated surfaces.

Another fundamental category of nanomaterials extensively utilized in cultural heritage protection is titanium dioxide (TiO_2). TiO_2 is very well-known for its photocatalytic properties, notably reducing the environmental degradation. When applied as a thin coating, TiO_2 serves as a protective barrier against UV radiation and pollutants [40] and microbial growth [74]. Both SiO_2 and TiO_2 nanoparticles have been formulated together, mainly to combine the hydrophobic properties of the SiO_2 and the catalytic effect of the TiO_2 [72,73,75].

Also, nanocellulose-based materials are arousing growing interest for the protection of cultural heritage. Fornari et al. [76] reviewed the application of nanocellulose for the restoration of wood artifacts, paintings, and ancient papers. As many collections of artistic patrimony are made of cellulose-based materials, interventions with these materials certainly give better results compared to synthetic products, and, moreover, they do not alter the optic effects of artistic surfaces.

Other innovative alternatives to traditional formulations and treatments are based on graphene and graphene-related materials (GRMS) [77]. The GRMs' unique properties make them excellent candidates for protective performance, including anti-corrosion, UV-aging resistance, or impermeability. Galvagno et al. [78] reviewed the use of graphene and GRMs in cultural heritage. They stated that the research works on GRMS for this purpose are still limited and much work has to be conducted in the coming years. However, they outlined the most relevant applications across various materials and substrates. Graphene has been shown to serve as an effective protective coating for paintings and figurative art [79], offering barriers against light, oxygen, moisture, and other harmful agents while demonstrating reversibility in the treatments. Apart from GRMS, Kotsidi et al. [80] also investigated other 2D innovative materials for the protection of dyes and inks, like tungsten disulfide (WS_2), molybdenum disulfide (MoS_2), and hexagonal boron nitride (hBN).

3.6.3. Green Chemistry/Nature-Based Solutions

Preserving cultural heritage is not only about safeguarding the past, but also about ensuring a sustainable future. The conventional practices employed in cultural heritage conservation often involve the use of highly toxic and poorly biodegradable compounds [81]. Unfortunately, these substances pose a risk not only to the materials being treated, but also to the environment. Therefore, introducing a more sustainable approach to the preservation of cultural materials is required [82].

In recent years, the adoption of green chemistry principles has revolutionized conservation practices, leading to the development of environmentally friendly materials that minimize harm to both heritage artifacts and the surrounding ecosystem. While certain advanced materials currently meet sustainability standards, there is significant opportunity and necessity to transition them into fully green approaches [83] that achieve the requirements outlined in the European Green Deal. Considering this, the development of innovative, eco-friendly products has become imperative, and particular attention is being dedicated to "green" chemistry systems using low-toxicity solvents, natural compounds, or bio-based/waste materials [5].

Recent advancements in conservation science offer promising alternatives to conventional treatments, and innovative materials derived from nature have been introduced, such as chitosan [50], nano-cellulose [76], and oils [84,85]. These materials adhere better to sustainability standards and exhibit better compatibility with historical substrates.

Biopolymers have emerged as versatile materials for consolidating and protecting cultural heritage materials [86,87]. Derived from natural sources like plant extracts, proteins, and polysaccharides, biopolymers can offer compatibility with historical substrates and exhibit excellent adhesive properties. Biopolymer-based consolidants and coatings provide mechanical reinforcement, stabilize fragile structures, and offer protection against environmental factors such as moisture, UV radiation, and microbial degradation. Furthermore, biopolymers offer the advantage of biodegradability, ensuring long-term compatibility with cultural artifacts and minimizing environmental impact [88].

Another key aspect of green chemistry in cultural heritage conservation is the use of environmentally friendly solvents for cleaning and restoration. Traditional organic solvents such as chlorinated hydrocarbons and petroleum-based compounds can cause irreversible damage to the surfaces and even contribute to air and water pollution. In contrast, green solvents offer effective alternatives with reduced environmental impact. These solvents not only facilitate the gentle removal of dirt, pollutants, and coatings, but also promote the preservation of original materials and surface integrity.

A notable class of green solvents is Deep Eutectic Solvents (DESs). These solvents have unique chemical–physical characteristics, including being non-toxic, biodegradable, nonflammable, and stable in the presence of water [82,89]. The most common components used for DESs are choline chloride (ChCl) or urea as hydrogen bond acceptors (HBA) and glucose or oxalic acid as hydrogen bond donors (HBD). Several DESs documented in the literature have demonstrated biocidal and inhibiting action against some bacteria [90], especially against Gram-positives and eukaryotic microorganisms, mainly fungi [91]. Moreover, DES have also been employed to dissolve and harvest biopolymers [90].

In many cases, it is nature itself that acts as a deteriorating agent, which is known as biodeterioration. The existing literature on biodeterioration and biocide treatments is extensive, while simultaneously, a new trend on bioprotection is emerging. These innovative approaches to microbial control in conservation focus on natural or sustainable biocides that prevent microbial attachment or disperse existing colonies without harmful effects [92]. Research highlights the efficacy of plant essential oils and other natural biocides in safeguarding stone cultural heritage [93]. Ashraf et al. [94] reviewed the use of green biocides such as enzymes or laser techniques and their applications in the industry that could be extended to the field of cultural heritage.

This emphasis on adopting green chemistry and exploring innovative compounds showcases a commitment to not only safeguarding cultural heritage, but also minimizing the ecological footprint associated with conservation and restoration efforts, thus ensuring the longevity and integrity of our cultural heritage.

4. Conclusions

This study applied bibliometric methodology to systematically map scientific research on cultural heritage conservation and protection using data retrieved from the Scopus database. The analysis was conducted with VOSviewer software and LDA methodology, and the annual publications, countries, most-cited publications, authors, institutions, and keywords were comprehensively analyzed, leading to the detection of hot topics and research trends.

The results showed a rising trend in the number of studies, particularly since 2010. Italy, home to the largest number of UNESCO heritage sites, is the most prolific country in this field. Significant progress has been made in understanding the deterioration processes, and there is growing interest in developing diverse treatments to protect these invaluable assets. Understanding deterioration mechanisms is crucial for accurate diagnostics, and innovative conservation treatments have emerged, prioritizing minimally invasive techniques to maintain authenticity while mitigating deterioration. Topics identified in the current research are expected to continue to grow, such as non-invasive analytical techniques and the use of nanotechnology and nature-based solutions for conservation.

Future research should focus on understanding the impact of climate change on cultural heritage; integrating AI-based techniques; and adopting multidisciplinary approaches that include natural and digital sciences, sustainable development, and advanced infrastructures. Additionally, analyzing funding trends and policy changes, as well as increasing public engagement and education, will be important.

These recommendations aim to provide more targeted and effective conservation strategies, improved diagnostic techniques, and a greater understanding of global challenges such as climate change, ensuring the preservation of cultural heritage for future generations.

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