

Article

Energy-Efficient Restoration of Historic Buildings: Mapping Decarbonization, Conservation-Compatible Retrofit Strategies, and Sustainable Tourism with Implications for Stone Places of Worship

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Abstract

Historic buildings occupy a sensitive position in contemporary energy and heritage management because they combine building-performance requirements, material-conservation constraints, and dynamic patterns of use. This study maps the broader historic-building literature at the intersection of energy-efficient restoration, building decarbonization, heritage conservation, and sustainable tourism, and interprets the resulting bibliometric structure with particular implications for historic stone places of worship. Records were retrieved from the Web of Science Core Collection and screened through a PRISMA 2020-aligned protocol, yielding 804 publications. Accordingly, the 804-record corpus represents a broad historic-building and heritage-management evidence base rather than an exhaustive dataset restricted exclusively to stone religious buildings. Performance analysis and science mapping were conducted using Bibliometrix, while bibliographic coupling and longitudinal thematic-evolution analyses were added to examine contemporary research fronts and their temporal continuity. Co-citation analysis identified two partially separated intellectual schools—European conservation microclimate and adaptive reuse management—whereas bibliographic coupling revealed five current research-front communities, including adaptive reuse and sustainability, microclimate-conservation-energy, and an emerging HBIM/digital-documentation front. Thematic evolution showed increasing post-2019 convergence of tourism and management with conservation and cultural-heritage research, but continued separation from technical energy and microclimate streams. The study therefore moves beyond descriptive rankings to identify structural fragmentation and three priority directions: integrated monitoring of visitor loads, energy, and conservation performance; HBIM-supported spatial integration; and stronger cross-national research collaboration. The findings are interpreted as bibliometric evidence and research-agenda signals rather than as causal proof of building or policy performance.



Academic Editor: Lambros T. Doulos

Received: 15 July 2026

Revised: 14 August 2026

Accepted: 18 August 2026

Published: 20 August 2026

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Keywords: historic stone buildings; building decarbonization; energy efficiency; places of worship; sustainable tourism; bibliometric analysis; conservation-compatible retrofit

1. Introduction

Stone places of worship are both heritage assets and living public buildings. Churches, mosques, cathedrals, monasteries, and temples preserve pre-industrial construction knowledge and sacred identity while also functioning as major heritage-tourism destinations [1–5]. Their dual role makes them a particularly demanding building type for conservation and energy management.

Heritage structures face a persistent tension between conservation requirements and contemporary performance expectations. International conservation frameworks require authenticity, material compatibility, and reversibility [6], whereas active and heavily visited religious buildings must also manage indoor air quality, thermal comfort, energy use, and sharp occupancy peaks. HVAC upgrades, thermal-management measures, or airtightness interventions can therefore be considered only when they remain compatible with conservation targets [7,8].

The resulting literature is intrinsically interdisciplinary but fragmented. Building-energy studies emphasize physics and thermodynamics; conservation research prioritizes authenticity and material integrity [9]; and tourism research addresses visitor flows, experience, and economic value [3,10]. Few studies systematically map how these traditions connect, where they remain separate, and which interfaces are sufficiently mature to support integrated research on stone places of worship.

Bibliometric science mapping can reveal this structure by combining performance indicators with co-word, co-citation, collaboration, coupling, and longitudinal thematic analyses [11–13]. This is particularly useful for interdisciplinary domains in which research communities may address related problems through different vocabularies, evidence bases, and publication venues.

This study addresses that gap using 804 Web of Science Core Collection records spanning 1983–2026. The analysis examines the intersection of energy-efficient restoration, sustainable conservation, and heritage tourism in historic buildings, with particular implications for stone places of worship. Accordingly, stone places of worship constitute the principal application and interpretation context of the study, rather than the exclusive building type represented in the bibliometric corpus. Its objective is not only to describe publication patterns, but also to identify intellectual separation, current research fronts, temporal thematic convergence, and evidence-grounded priorities for future interdisciplinary work.

Four primary research questions structure the analysis: (RQ1) What is the intellectual and social structure of research at this interdisciplinary nexus? (RQ2) What are the bibliometric regularities of growth, source concentration, and author productivity? (RQ3) What are the dominant and emerging thematic clusters and current research fronts, and how have they evolved over time? (RQ4) What research gaps and integration priorities does the broader historic-building literature reveal for tourism-compatible, energy-efficient restoration of stone places of worship?

Section 2 describes corpus construction, the interpretive thermodynamic framework, and the bibliometric methods. Section 3 reports performance analysis, science mapping, bibliographic coupling, and thematic evolution. Section 4 develops the implications for interdisciplinary integration, and Section 5 summarizes the main contributions, limitations, and research priorities.

2. Materials and Methods

2.1. Data Collection and PRISMA-Compliant Screening Protocol

This research is based on a transparent and reproducible bibliometric workflow implemented in R (version 4.6.1) using Bibliometrix (R) (version 5.4.1) and its biblioshiny graphical interface [11], also following established bibliometric guidelines [12,13]. Biblio-

graphic records were obtained from the Web of Science Core Collection (SCI-Expanded, SSCI, ESCI) through a structured topic-level (TS=) search combining three conceptual blocks: (1) type of building (historic/heritage/stone buildings, religious structures such as churches, mosques, cathedrals, monasteries, and temples), (2) energy and conservation interventions (energy retrofit, energy efficiency, thermal performance, sustainable conservation, restoration), and (3) use context (tourism, heritage tourism, cultural tourism, visitors, adaptive reuse, museum). The definitive search query was structured as follows:

TS = (("historic building*" OR "heritage building*" OR "historic masonry" OR "stone heritage" OR "religious heritage" OR "religious building*" OR church* OR mosque* OR cathedral* OR monastery OR temple*) AND ("energy retrofit*" OR "energy renovation*" OR "energy efficiency" OR "energy performance" OR "thermal performance" OR "sustainable conservation" OR restoration OR conservation) AND (tourism OR "heritage tourism" OR "cultural tourism" OR visitor* OR "adaptive reuse" OR museum*)).

The search terms were designed to achieve broad and reproducible coverage of the target research intersection without over-specifying individual building typologies or methodological approaches. Several terms suggested in peer review were considered but were not retrospectively added because changing the retrieval query after corpus construction would alter the analyzed dataset. "Basilica" was treated as an architectural subtype that is generally covered by broader church, cathedral, and religious-building terminology, although the strategy does not claim exhaustive retrieval of papers that use only "basilica". "Thermal comfort" was not used as a stand-alone retrieval term; thermal-comfort studies entered the corpus when they also matched the existing energy/conservation and building/use-context blocks, so the corpus should not be interpreted as exhaustive for thermal-comfort research. Software names such as DesignBuilder, EnergyPlus, TRNSYS, IDA-ICE, or OpenStudio were not used as mandatory search terms because they identify tools rather than the substantive research domain and would privilege particular simulation environments. Likewise, "sustainability AND historic buildings" and descriptors of high-volume interiors were not imposed as additional mandatory terms because the query was structured around broader typological, intervention, and use-context concepts. The term "museum*" was retained because museum microclimate and preventive-conservation studies provide technically relevant evidence for historic religious buildings. Subject-category filtering and manual relevance screening were then used to remove out-of-scope records.

Importantly, the retrieval query and the subsequent science-mapping vocabulary served different functions. The query defined which records entered the corpus, whereas the mapping analyses used bibliographic keyword fields contained in the included records, with field choice and normalization specified for each analysis below. The standard co-word and strategic thematic analyses were therefore not limited to the words used in the search string, and the added longitudinal thematic-evolution analysis used the combined normalized Author Keywords and Keywords Plus fields described in Section 2.2.3. Consequently, concepts such as "visitor management" and "energy monitoring" could emerge, or their weak co-occurrence could be observed, even though they were not explicitly specified as retrieval terms.

The Web of Science Core Collection search was conducted on 15 February 2026. The archived Full Record & Cited References file used for the present analyses was exported on 26 May 2026; the export date is reported separately from the search date. No lower publication-year restriction was applied. The initial search returned 1247 records across all document types. These records were reviewed according to a PRISMA 2020-aligned workflow adapted for bibliometric studies [14], as summarized in Figure 1. Four filtering steps were applied after identification. First, records lacking an Article or Review designation were excluded. Hybrid Web of Science records that retained an Article designation

(e.g., Article; Proceedings Paper, Article; Early Access, or Article; Book Chapter) were kept, whereas conference-only papers, editorials, book reviews, letters, and other non-Article/Review records were removed. This step removed 212 records, leaving 1035 items. Second, non-English records were removed to ensure consistency in bibliographic parsing, keyword processing, and text-field standardization, leaving 862 records. Third, a Web of Science subject-category filter was applied to exclude records outside the built environment, conservation, energy, tourism, and cultural-heritage scope. This step removed 48 records, leaving 814 records. Fourth, the remaining records were manually checked at the title, abstract, and keyword levels to remove false positives. This manual relevance screening excluded 10 records that used terms such as “conservation”, “heritage”, or “restoration” in contexts not directly relevant to the research scope. The manually excluded records were mainly cases in which the search terms appeared in a marginal or metaphorical sense without a clear connection to built heritage, energy/conservation intervention, or visitor-related use. The final corpus therefore consisted of 804 publications. Two authors resolved borderline cases by consensus. Before analysis, author names, affiliations, and countries were harmonized. Keyword handling was analysis-specific: the descriptive Bibliometrix outputs retained source-level keyword forms, while the advanced longitudinal analysis applied canonical case/spacing normalization and duplicate removal within documents. This distinction is reported explicitly because hyphenated or otherwise variant keyword forms may remain separate in the descriptive frequency output.

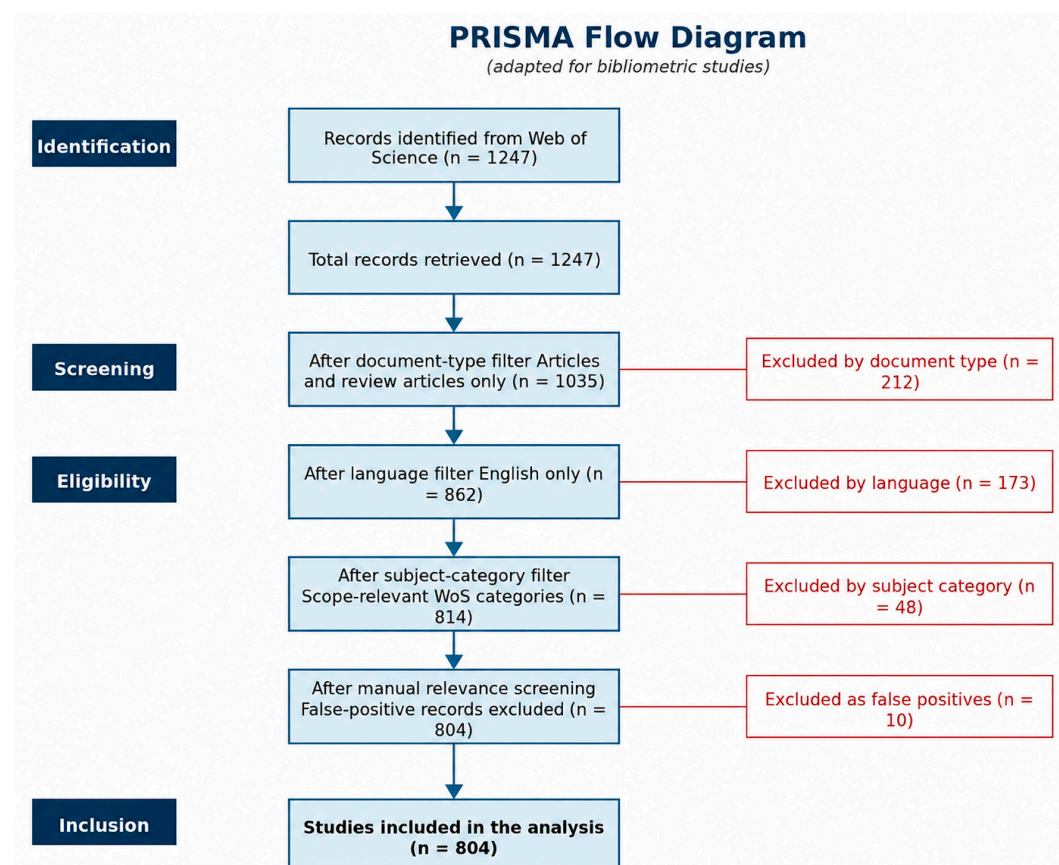


Figure 1. PRISMA 2020-aligned screening flow used to construct the bibliometric corpus. Records retrieved from the Web of Science Core Collection were filtered in four steps after identification: document type, language, Web of Science subject category, and manual relevance screening for false-positive records. This process excluded ineligible and out-of-scope records, resulting in a final analysis corpus of 804 publications.

2.2. Interpretive Thermodynamic and Informetric Framework

The bibliometric analysis is the primary analytical instrument of this study. Equations (1) and (2) are retained solely as a compact interpretive physical framework; they are not fitted to measured building data and are not used to generate bibliometric indicators. Their analytical value is to make explicit the physical mechanisms connecting thematic areas that appear partly separated in the bibliometric maps. Equation (1) represents the transient thermal behavior and thermal inertia of historic masonry underlying microclimate and conservation–energy studies, whereas Equation (2) represents occupancy-related sensible and latent heat gains that make visitor intensity relevant to indoor environmental and energy performance. Thus, these equations do not constitute an independent engineering model; rather, they provide a physical rationale for interpreting why microclimate, energy-performance, conservation, and visitor-management themes belong to the same building-operation problem even when their bibliometric linkage is weak. The informetric models in Section 2.2.2, by contrast, are applied directly to publication and citation data.

2.2.1. Interpretive Thermodynamic Context: Transient Heat Transfer and Occupancy Loads

Two compact physical relations are used here only to contextualize the bibliometric interpretation. First, the transient thermal behavior of heavy historic masonry can be represented by the one-dimensional heat-conduction relation:

$$\rho C_p \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} \quad (1)$$

where ρ represents the structural density of the stone material (kg/m^3), C_p is the specific heat capacity (J/kgK), λ is the material thermal conductivity (W/mK), T is the local temperature (K), t is time (s), and x is the spatial coordinate along the wall thickness (m). Second, episodic visitor occupancy introduces an additional operational load that is relevant to both indoor microclimate and energy performance. Its instantaneous sensible and latent contribution can be expressed generically as:

$$Q_{total} = N_{tourist}(q_s + q_l) \quad (2)$$

where $N_{tourist}$ represents the time-dependent visitor occupancy profile, q_s is the representative sensible heat gain per visitor, and q_l is the representative latent heat gain per visitor. No site-specific numerical values are assigned because Equation (2) is used only to clarify the physical relationship between visitor intensity and building-energy/microclimate operation, rather than to calculate thermal loads for a particular building.

2.2.2. Informetric Formulations and Field Growth Regularities

To assess publishing concentration, author productivity dispersal, and cumulative expansion patterns across the final 804 publications, three distinct informetric regularities were quantified:

1. Author Productivity Dispersal (Lotka's Inverse Power Law): The frequency distribution of scientific productivity within the interdisciplinary corpus was modeled using least squares regression via [15]:

$$Y = \frac{C}{X^\beta} \quad (3)$$

where X is the specific number of publications produced by an author, Y is the empirical proportion of authors achieving X documents, C is a structural constant, and β is the estimated power exponent determining the productivity drop-off rate.

The agreement between the observed and predicted distribution was tested using the Kolmogorov–Smirnov (KS) test.

2. Journal Concentration Profiling (Bradford’s Law): To determine source base concentration, the publishing distribution was parsed into three concentric zones of decreasing productivity using the mathematical multiplier curve [16]:

$$C(r) = a + b \cdot \log(r) \quad (4)$$

where $C(r)$ is the cumulative number of articles published up to journal rank r , with the multiplier k estimated directly from zone boundaries.

3. Exploratory Cumulative Growth Modeling: As a supplementary descriptive analysis under RQ2, a logistic curve was fitted to the cumulative annual publication series for 1983–2024. The model is retained only to summarize the observed shape of cumulative growth; it is not used to infer lifecycle maturity, structural saturation, or future publication volume. Records from 2025 to 2026 were excluded from fitting because indexing for these years was incomplete at the search date.

$$P(t) = \frac{K}{1 + e^{-r(t-T_m)}} \quad (5)$$

where $P(t)$ represents cumulative publication volume at time t , K is the asymptotic parameter of the fitted logistic curve ($K = 1238$), r is the fitted growth coefficient, and T_m is the inflection parameter ($T_m = 2025$). K is treated only as a mathematical fit parameter and not as a real carrying capacity or saturation threshold. Fit statistics were AIC = 165.5 and BIC = 170.0.

The last step resolved the conceptual and intellectual structuring of the literature. Keyword co-occurrence analysis identified recurrent conceptual links. Thematic mapping was interpreted using Callon’s density–centrality framework [17,18]. Citation analysis was used to track common intellectual underpinnings, and co-authorship analysis was employed to examine collaborative behavior at the author and national levels. Unless a particular study required a different approach, the network analyses employed complete counting. Link weights were normalized using association strength, and clusters were identified using modularity-based community identification [19]. Criteria for thresholds, such as minimum keyword occurrences, time-slice bounds, and network inclusion, were established before interpretation. These parameters are presented in Table 1 to ensure transparency and replicability of the analytical procedure.

Table 1. Integrated analytical parameters and full informetric disclosure.

Parameter	Value/Setting
Search window	1983–15 February 2026 search; final export 26 May 2026
Database	Web of Science Core Collection (SCI-E, SSCI, ESCI)
Language filter	English only
Export format	Full Record & Cited References
Document types included	Records designated Article or Review; hybrid Article labels retained
Records excluded (doc type)	$n = 212$ records without Article/Review designation (conference-only papers, editorials, book reviews, etc.)
Records excluded (language)	$n = 173$ (non-English)
Records excluded (subject category)	$n = 48$ (biology, legal sciences, and other out-of-scope WoS categories)
Records excluded after manual relevance screening	$n = 10$ (false-positive records after title, abstract, and keyword check)

Table 1. Cont.

Parameter	Value/Setting
Manual relevance screening	Title, abstract, and keyword-level check
Final corpus	$n = 804$
Keyword normalization	Analysis-specific: source-level forms retained in descriptive outputs; canonicalized combined keyword fields used for longitudinal evolution
Co-word threshold	Minimum keyword occurrence threshold = 3; unique per document
Co-word normalization	Association-strength; full counting
Growth model	Logistic cumulative-growth fit to annual cumulative publication output; exploratory / descriptive use only
Thematic periods	Pre-2010; 2010–2018; 2019–2026
Software	R 4.6.1; Bibliometrix 5.4.1/biblioshiny; Python 3.13.5; NetworkX 3.6.1 for coupling and thematic-evolution extension
Lotka's Law fitting	Inverse power law (least squares regression)
Bradford's Law fitting	Bradford curve; multiplier k estimated from zone boundaries
Co-authorship network threshold	Min. 2 publications per author; at least 1 co-authored document per author pair (to reduce noise while preserving core collaborations)
Co-word threshold justification	Min. 3 occurrences per keyword, selected to balance network coverage and low-frequency noise in the 804-record corpus
Bibliographic coupling	Document level; cited-reference canonicalization by DOI or author-year-source-volume-page
Coupling normalization/threshold	Salton cosine; ≥ 2 shared references and normalized strength ≥ 0.05 ; selected to exclude single-reference coincidences and very weak normalized ties while preserving an interpretable network backbone
Coupling community detection	Louvain, resolution = 0.4, selected to identify meso-scale research fronts while limiting excessive cluster fragmentation; largest backbone $n = 328$ documents, 2769 links; $Q = 0.512$
Thematic-evolution periods	1983–2009; 2010–2018; 2019–2026
Thematic-evolution basis	Top 40 normalized keywords per period, fixed across periods to maintain comparable network size and limit sparse low-frequency noise; Louvain communities; inter-period continuity by shared normalized keywords

2.2.3. Advanced Bibliometric Extension: Bibliographic Coupling and Thematic Evolution

To move beyond standard performance and co-occurrence outputs, two complementary analyses were performed on the same final 804-record Full Record & Cited References export. First, document-level bibliographic coupling was calculated from shared cited references [20]. References were canonicalized by DOI when available and otherwise by first author, year, source, volume, and page. For each document pair, coupling strength was normalized using the Salton cosine, $c_{ij}/\sqrt{R_i R_j}$, where c_{ij} is the number of shared references and R_i and R_j are the numbers of unique cited references in the two documents. To suppress incidental overlap, links were retained only when documents shared at least two references and the normalized coupling strength was at least 0.05. These thresholds were used as conservative screening criteria to reduce incidental citation overlap while retaining an interpretable network backbone. Requiring at least two shared references excludes links based on a single coincidental reference, whereas the normalized-strength threshold removes very weak similarities without restricting the network only to a small high-density core. The largest connected backbone contained 328 documents and 2769 links. Louvain community detection (resolution = 0.4) was then applied to identify contemporary research-front communities. The resolution parameter was set to 0.4 to favor interpretable meso-scale communities representing broad contemporary research fronts and to reduce excessive fragmentation into numerous small clusters, consistent with the study's objective of identifying major structural fronts rather than fine-grained subcommunities.

Second, thematic evolution was evaluated across three periods aligned with the longitudinal structure of the corpus (1983–2009, 2010–2018, and 2019–2026). In each period, a co-word network was constructed from the 40 most frequent normalized keywords

drawn from the combined author-keyword and Keywords Plus fields, with duplicate terms counted once per document. A fixed Top-40 cutoff was used across all periods to maintain a comparable network size over time while limiting the influence of sparse, low-frequency terms; the cutoff therefore serves as a transparent dimensionality-control rule rather than implying that terms below rank 40 are substantively unimportant. Period-specific networks were clustered with the Louvain algorithm, and continuity between adjacent-period communities was measured by shared normalized keywords. This extension complements co-citation analysis: co-citation traces the historical intellectual base, bibliographic coupling maps current research fronts through shared references, and thematic evolution reveals persistence, splitting, and convergence of conceptual communities over time. The added network calculations were implemented in Python 3.13.5 using NetworkX 3.6.1.

3. Results

3.1. Annual Scientific Production and Field Growth Dynamics

Figure 2a,b illustrate the annual publication output and the average citations per year within the investigated domain from 1983 to 2026. The longitudinal publication trajectory indicates a prolonged baseline phase of limited scholarly activity, followed by a noticeable expansion after 2010 and an accelerated surge following 2019. Specifically, the annual output remained below 10 articles prior to 2010, grew to approximately 30 publications in 2018, and subsequently peaked at approximately 130 publications in 2025. The lower volume recorded for 2026 must be interpreted with caution, as data collection transpired prior to the completion of the 2026 indexing cycle, meaning recent contributions were not yet fully indexed within the database.

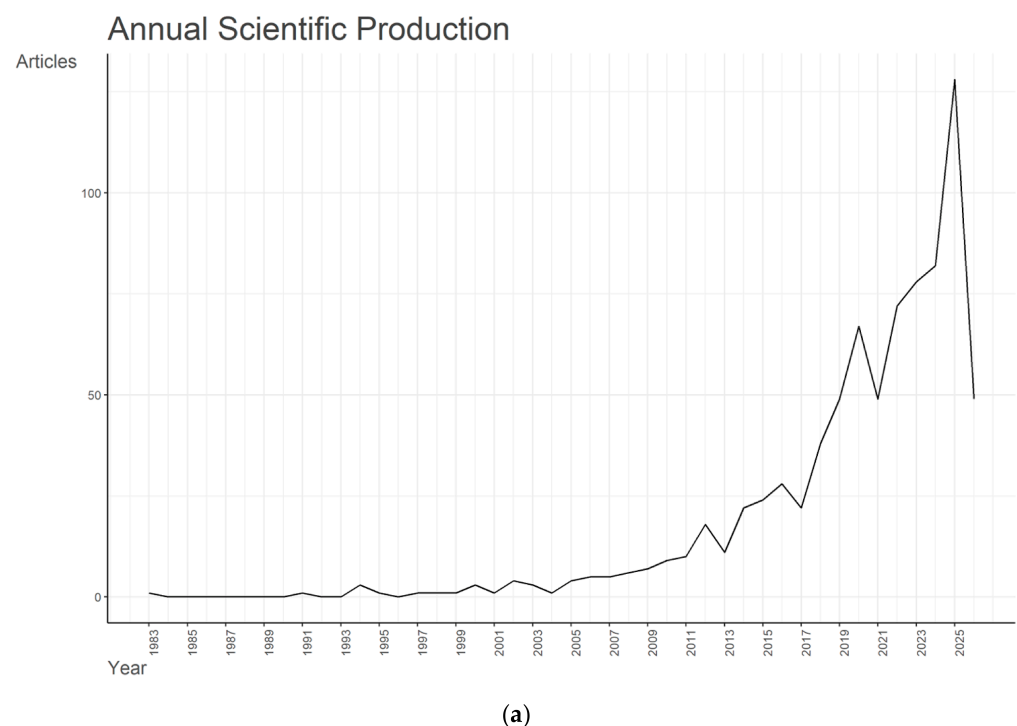


Figure 2. Cont.

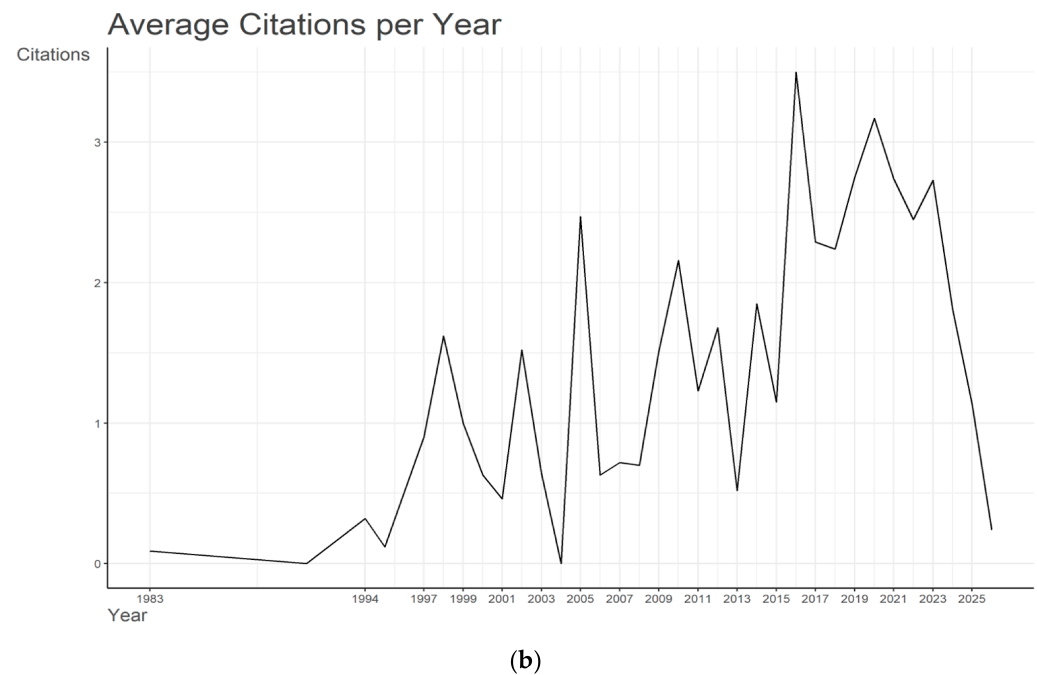


Figure 2. (a) Annual publications in the final corpus of 804 records, 1983–2026. The data indicate low output before 2010, a slow rise in 2010–2018, and a sharp increase from 2019 onwards, with the highest indexed yearly output recorded in 2025. The 2026 value represents a partial observation because the indexing cycle was incomplete at the time of data retrieval. The recent 2025–2026 records were shown in the annual production analysis but were not included in the cumulative-growth model fit. (b) Average citations per year for publications in the study corpus, 1983–2026. Higher values in earlier and mid-period years reflect the longer citation accumulation window, while the lower values for 2023–2026 should be read in relation to citation and indexing lag.

The citation pattern follows an inverse temporal logic: earlier and mid-period publications have had a longer exposure window in which to accumulate citations, whereas recent papers are affected by citation lag. The sharp post-2019 increase in publication output occurs contemporaneously with stronger policy and research attention to building decarbonization, heritage adaptation, and post-pandemic tourism recovery; however, the bibliometric time series alone does not establish a causal relationship between these external developments and publication growth.

Figure 3 presents the exploratory logistic fit as a compact description of the observed cumulative publication series. The curve was fitted only to 1983–2024, while incomplete 2025–2026 records are shown separately. The fit yielded $R^2 = 0.883$, $RMSE = 10.43$, $AIC = 165.5$, and $BIC = 170.0$. The estimated K value of 1238 is reported solely as an asymptotic model parameter; the ratio of the current corpus to K is not interpreted as evidence of saturation or as a forecast. The model therefore provides contextual information for RQ2 but is not used to derive the study’s structural conclusions or research priorities.

3.2. Bibliometric Regularities: Lotka’s Law and Bradford’s Law

Figure 4 displays the parametric evaluation of author productivity dispersal compiled via Lotka’s Law. The calculated model parameters ($\beta = 3.34$; $C = 0.6881$; $R^2 = 0.9592$) reveal a strong inverse power-law structure. The non-parametric Kolmogorov–Smirnov test supports the robustness of the fitted distribution, yielding a high KS p -value of 0.988. Conversely, running the KS test against the classical inverse-square formulation ($\beta = 2$) results in a statistically significant deviation ($p = 0.0149$), falling well below the standard alpha threshold ($\alpha = 0.05$).

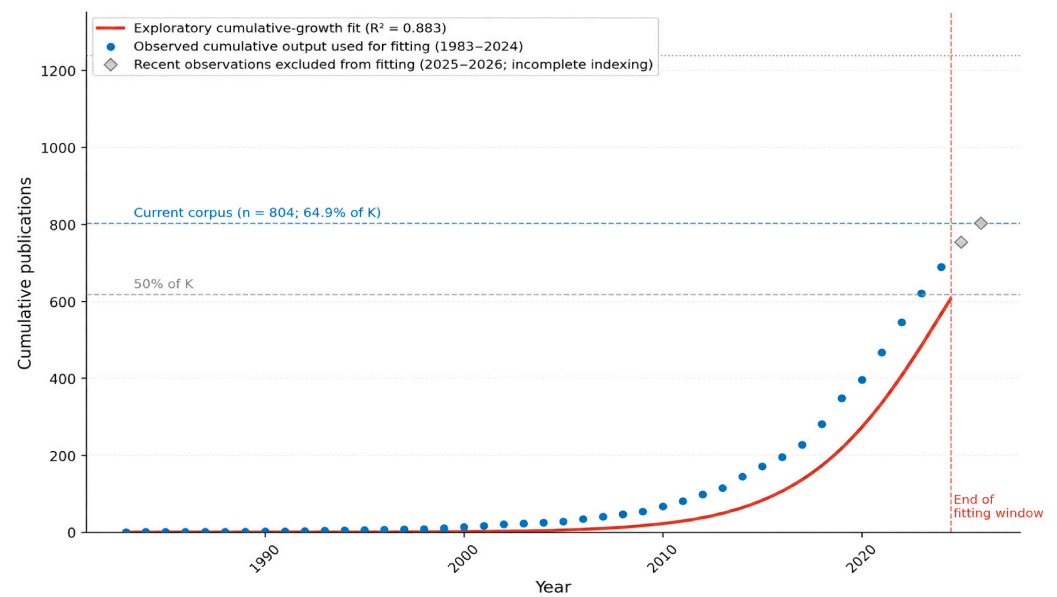


Figure 3. Exploratory cumulative-growth fit to publication output in the final corpus. The logistic curve was fitted only to the observed cumulative series for 1983–2024. Records indexed for 2025–2026 are shown separately as recent observations affected by incomplete indexing and were therefore excluded from model fitting. The horizontal reference lines indicate 50% of the estimated K value and the position of the current corpus ($n = 804$; 64.9% of K). The figure is presented as a descriptive summary of the cumulative publication series and not as a forecast of future output.

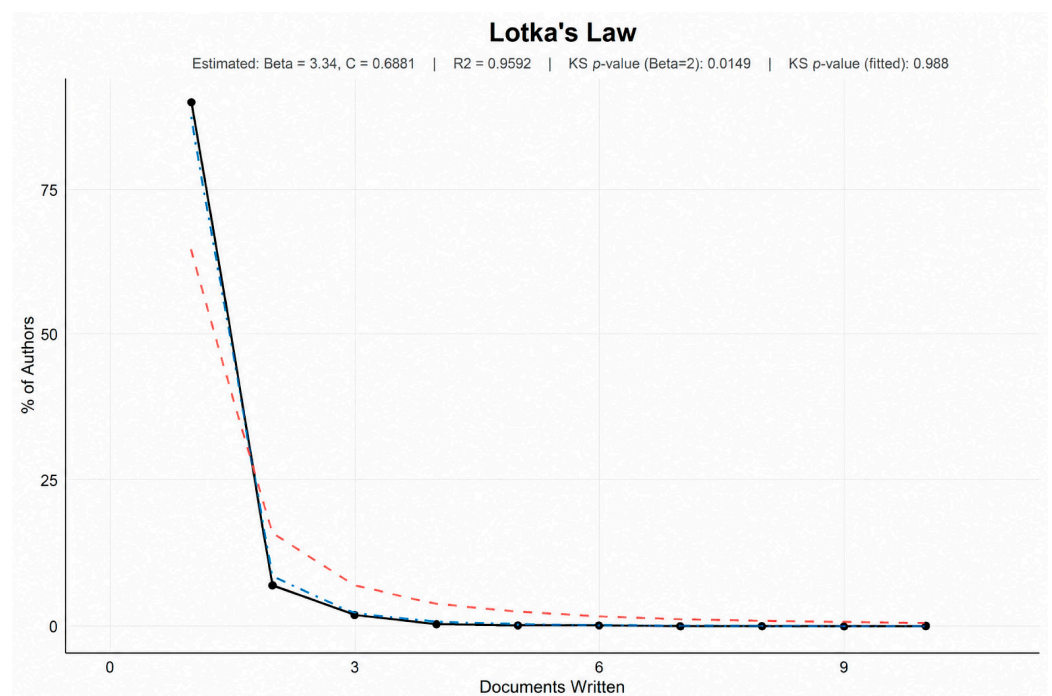


Figure 4. Lotka's Law analysis of author productivity. The estimated $\beta = 3.34$ ($R^2 = 0.959$) is higher than the conventional inverse-square value ($\beta = 2$; $KS\ p = 0.0149$), indicating a steeper productivity decline than predicted by the classical Lotka model. The black solid line with markers represents the observed author-productivity distribution, the blue dashed line represents the fitted Lotka model ($\beta = 3.34$), and the red dashed line represents the classical inverse-square reference ($\beta = 2$).

This statistical divergence confirms a distribution profile more asymmetrical than classical informetric assumptions project: the steep power exponent of $\beta = 3.34$ points to a highly concentrated productivity structure where a significant majority of authors (~90%) contribute only a single document to the domain, whereas a compact core of specialized researchers accounts for an outsized portion of the total scientific output. This productive nucleus is led jointly by Caciora, T. and Ilies, D.C. with 10 publications each, followed closely by Ilies, A. with 9 contributions.

The application of Bradford's Law regarding source distribution is presented in Figure 5. The empirical data align closely with the Bradford formulation ($R^2 = 0.9872$), yielding an estimated Bradford multiplier (k) of 4.31. Although the corresponding KS test ($p = 0.0249$) detects a formal statistical deviation from the theoretical curve—a common occurrence when modeling specialized, finite multi-disciplinary datasets—the exceptionally high coefficient of determination ($R^2 = 0.9872$) and the clear three-zone layout validate the descriptive utility of the model. The core zone (Zone 1) encompasses a highly concentrated group of merely 13 journals that index a disproportionately large share of the total literature. Zone 2 comprises 58 journals, while Zone 3 expands across 241 peripheral sources. The high value of the Bradford multiplier ($k = 4.31$) confirms a pronounced consolidation of the literature within the core nucleus. However, the wide disciplinary span of Zones 2 and 3 indicates that the research territory is shared across diverse fields, extending through sustainability, architectural conservation science, energy performance, heritage management, and sustainable destination engineering.

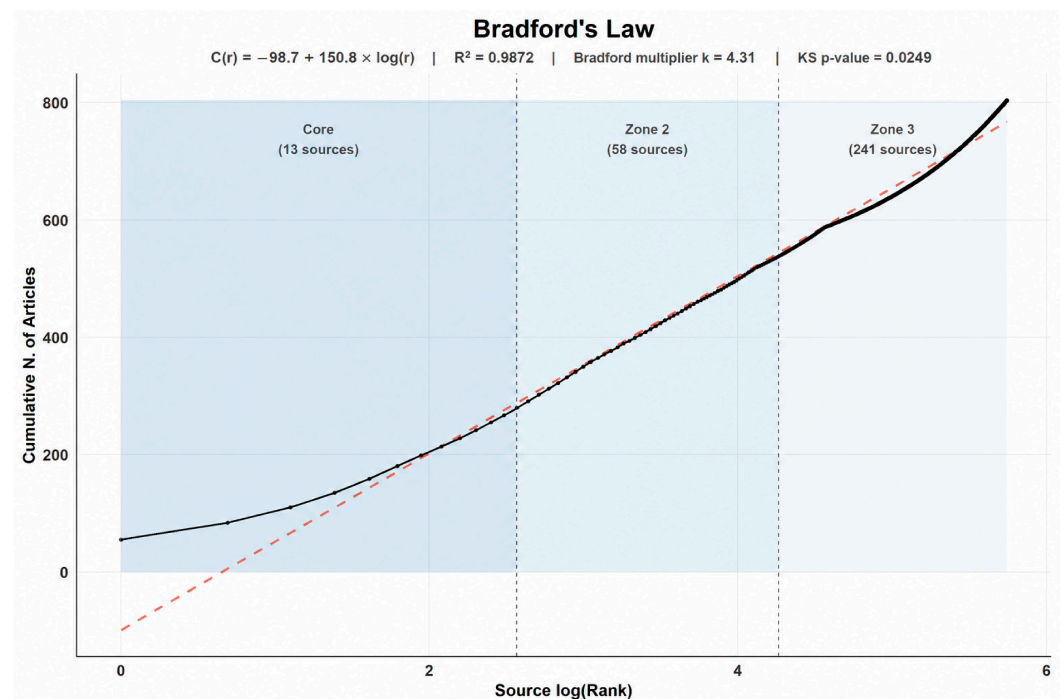


Figure 5. Analysis of journal concentration using Bradford's Law. The fitted Bradford curve ($R^2 = 0.9872$, $k = 4.31$; KS $p = 0.0249$) identified 13 core journals, 58 Zone 2 journals, and 241 Zone 3 journals. The black solid line represents the empirical cumulative source distribution, the red dashed line represents the fitted Bradford curve, and the vertical dashed lines indicate the boundaries between the Core, Zone 2, and Zone 3.

3.3. The Most Relevant Sources

The top 10 most prolific journals publishing within this interdisciplinary domain are mapped in Figure 6. Sustainability leads the ranking with 55 published articles, followed by Buildings with 29 contributions. The adjacent core venues consist of the Journal of Cultural Heritage (26 articles), Heritage (25 articles), and Studies in Conservation (24 articles).

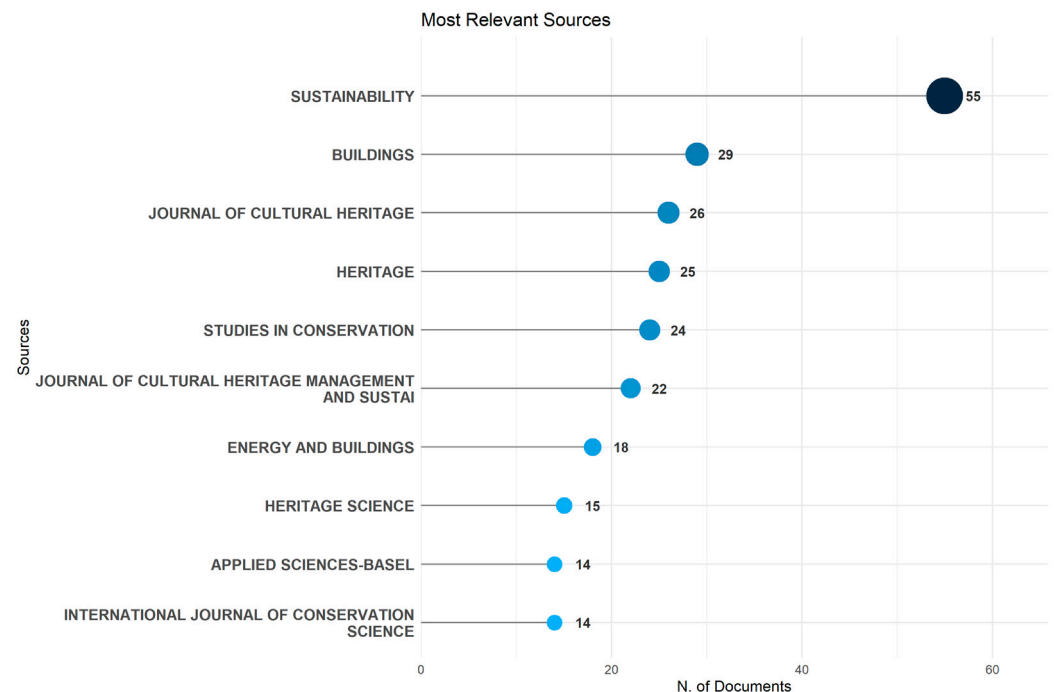


Figure 6. Journals with the highest publication output in the final corpus. Sustainability has the most records, followed by Buildings, Journal of Cultural Heritage, Heritage, and Studies in Conservation.

This distribution highlights the methodological structure of the field: outlets such as the Journal of Cultural Heritage Management and Sustainability (22 articles) represent the socioeconomic and administrative dimensions of heritage preservation, whereas Energy and Buildings (18 articles) provides the technical venue for thermodynamic modeling and structural performance optimizations. The presence of specialized platforms like Heritage Science (15 articles), Applied Sciences-Basel (14 articles), and the International Journal of Conservation Science (14 articles) further demonstrates that publishing activity is concentrated within a select group of journals that bridge material science, mechanical retrofitting, and environmental sustainability.

The bibliometric data themselves do not permit a causal determination of why authors selected particular journals. Nevertheless, the observed source distribution suggests several plausible structural explanations. The broad interdisciplinary scopes of Sustainability and Buildings accommodate research spanning heritage conservation, building science, and sustainability, whereas journals such as the Journal of Cultural Heritage, Studies in Conservation, and Energy and Buildings provide more discipline-specific outlets. The absence of a journal dedicated specifically to the intersection of energy performance, conservation, and historic religious buildings may further explain the dispersion of publications across these adjacent venues. Possible influences of publication speed, publisher characteristics, special issues, or guest editors cannot be established from the present dataset and would require a separate article-level or author-survey analysis.

3.4. Most Relevant Authors and Collaboration Networks

Figure 7 presents the ten most productive researchers in the dataset. The research group led by Caciora, T. (10 publications), Ilies, D.C. (10 publications), and Ilies, A. (9 publications) constitutes a highly active cluster primarily engaged in empirical energy performance monitoring and microclimate diagnostics within historical religious structures in Transylvania and the wider Carpathian region. Fabbri, K. and Lucchi, E. follow with 8 publications each, anchoring the highly influential Italian school of heritage energy analysis that pioneered microclimate-based preventive conservation frameworks. Wang, Y. (7 publications) introduces computational insights regarding historical building performance within the Asian context. The top ten is completed by Bratu, I., Grama, V., Marutoiu, C., and Silva, H.E., with 6 publications each. The former three cooperate with the active Romanian structural monitoring cluster, while Silva, H.E. represents the Portuguese school specializing in predictive indoor microclimate modeling and historical building diagnostics.

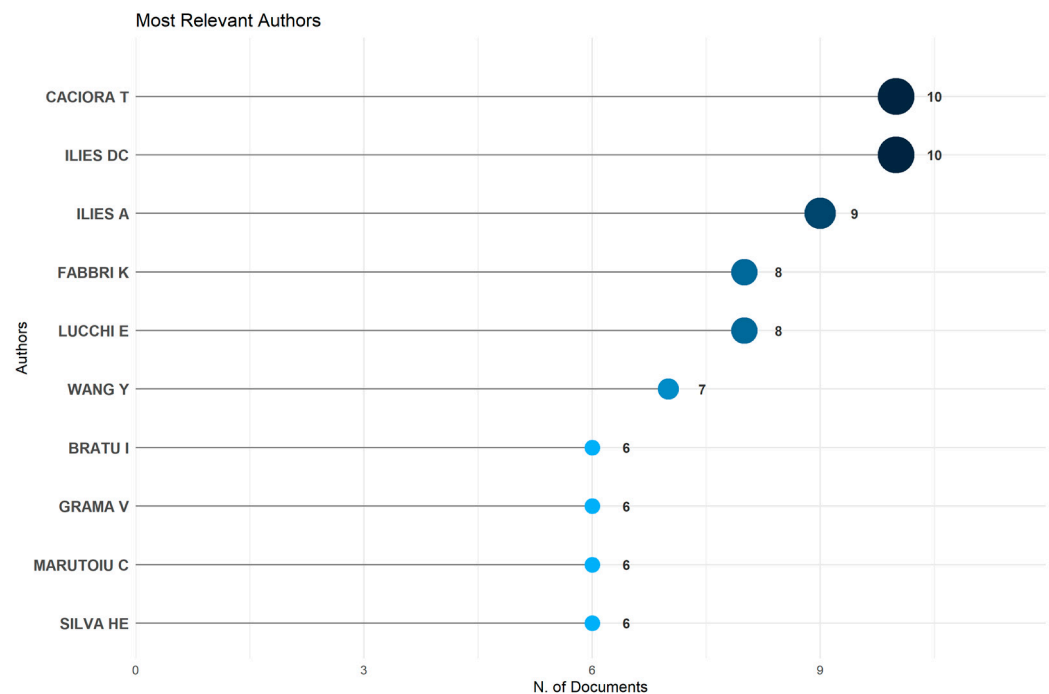


Figure 7. The ten most productive authors in the study corpus. Caciora, T., and Ilies, D.C. ($n = 10$ each) jointly lead, followed by Ilies, A. ($n = 9$).

The co-authorship network analysis reveals that scientific collaboration within this domain is structured around localized, regional hubs rather than a globally integrated network. The largest cluster is formed by Romanian researchers affiliated with the Caciora–Ilies group, while Italian and Spanish groups represent secondary nodes. Cross-cluster international co-authorship remains limited, confirming the structural isolation patterns observed in the corresponding-author country analysis. This fragmented collaboration topology suggests that the field has not yet developed the international multi-disciplinary research consortia required to advance the integration of energy engineering, conservation science, and tourism management.

3.5. Corresponding Author Countries and Regional Contributions

The geographical distribution of research outputs based on corresponding-author affiliations is concentrated in a relatively small group of countries. Italy ranks first with more than 120 publications, followed by China with approximately 90; the United Kingdom

(~55) and Turkey (~35) rank third and fourth. China also shows a visibly higher share of Multi-Country Publications (MCP) than Turkey. These affiliation-based counts describe national output and collaboration patterns, but the bibliometric data do not establish why publication volumes differ across countries.

Turkey records 35 contributions in the corpus, consisting of 34 Single-Country Publications (SCPs) and 1 Multi-Country Publication (MCP), corresponding to an international co-authorship rate of approximately 3%. This is a bibliometric observation of comparatively low international co-authorship relative to output volume. Turkey also contains a diverse stock of historic stone architecture—including Byzantine churches, Seljuk stone structures, and Ottoman mosques—which makes it a relevant context for future comparative heritage research; however, this contextual characteristic does not explain the observed MCP pattern. The underlying causes—whether funding structures, institutional priorities, language barriers, or other factors—cannot be determined from bibliometric data alone and would require targeted survey, interview, or policy-level evidence.

3.6. Most Cited Documents and Citation Mapping

The top 10 most globally cited papers within the analyzed dataset are mapped in Figure 8 and detailed in Table 2. Foster [10] ranks first with 365 global citations and represents the circular-economy and adaptive-reuse strand of the corpus. Martínez-Molina et al. [8] follow with 343 citations and provide a widely cited review of energy-efficiency and thermal-comfort interventions in historic buildings. Yung and Chan [4] have 289 citations and address stakeholder-centered adaptive reuse, while Misirlisoy and Günçe [9] have 235 citations and propose a holistic adaptive-reuse framework. These citation counts indicate visibility within the analyzed corpus and should not be interpreted as direct evidence of causal influence on practice or policy.

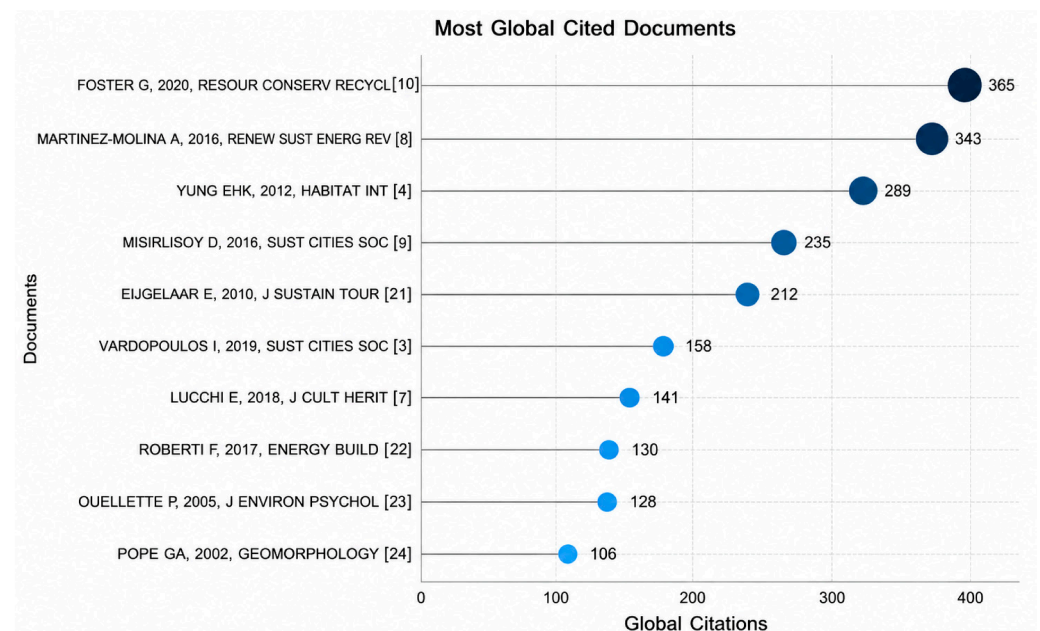


Figure 8. The ten most globally cited publications in the research corpus (total citations from Web of Science): Foster 2020 [10], Martínez-Molina et al. 2016 [8], Yung and Chan 2012 [4], Misirlisoy and Günçe 2016 [9], Eijgelaar et al. 2010 [21], Vardopoulos 2019 [3], Lucchi 2018 [7], Roberti et al. 2017 [22], Ouellette et al. 2005 [23], and Pope et al. 2002 [24].

Table 2. Top 10 most globally cited documents in the analytical corpus.

Authors	Year	Source	Global Citations
Foster, G. [10]	2020	Resources, Conservation and Recycling	365
Martínez-Molina, A. et al. [8]	2016	Renewable and Sustainable Energy Reviews	343
Yung, E.H.K. & Chan, E.H.W. [4]	2012	Habitat International	289
Misirlisoy, D. & Günçe, K. [9]	2016	Sustainable Cities and Society	235
Eijgelaar, E. et al. [21]	2010	Journal of Sustainable Tourism	212
Vardopoulos, I. [3]	2019	Sustainable Cities and Society	158
Lucchi, E. [7]	2018	Journal of Cultural Heritage	141
Roberti, F. et al. [22]	2017	Energy and Buildings	130
Ouellette, P. et al. [23]	2005	Journal of Environmental Psychology	128
Pope, G.A. et al. [24]	2002	Geomorphology	106

Eijgelaar et al. [21] have 212 citations and contribute a tourism-related carbon-accounting perspective. Vardopoulos [3] has 158 citations and addresses multi-criteria assessment for heritage adaptive reuse; Lucchi [7] has 141 citations and reviews preventive conservation and environmental monitoring in museum buildings; Roberti et al. [22] have 130 citations and examine multi-objective optimization for historic-building retrofit; Ouellette et al. [23] have 128 citations and address restorative qualities of monastic environments; and Pope et al. [24] have 106 citations and examine weathering processes in cultural stone. Together, these highly cited documents illustrate the disciplinary breadth of the corpus rather than a single linear pathway of influence.

3.7. Most Relevant Keywords and Conceptual Topology

The most frequent keyword terms in the Bibliometrix output are illustrated in Figure 9a. The term ‘conservation’ anchors the conceptual space with 229 mentions, indicating the central role of conservation vocabulary within the literature. ‘Adaptive reuse’ ranks second with 135 occurrences. The remaining high-frequency terms focus on the heritage–visitor and built-environment interface: ‘cultural heritage’ (85), ‘heritage’ (85), ‘tourism’ (72), ‘cultural-heritage’ (71), ‘sustainability’ (66), ‘historic buildings’ (65), ‘buildings’ (60), and ‘heritage buildings’ (58). Because descriptive frequency output retains source-level forms, hyphenated variants can appear separately.

Figure 9b delineates the keyword co-occurrence network constructed using association-strength normalization and a minimum frequency threshold of 3. The topology segregates into two principal structural macro-clusters. The red cluster gathers heritage administration and socio-operational concepts, including conservation, adaptive reuse, cultural heritage, tourism, sustainability, preservation, and urban regeneration. Conversely, the blue cluster consolidates technical building physics and environmental performance parameters, encompassing energy efficiency, historic buildings, museum, indoor microclimate, preventive conservation, thermal comfort, and deterioration.

The thresholded co-word network contains only a small set of bridging terms between the heritage-management and technical building-performance domains. The keyword “church” is positioned within the technical cluster alongside museum and indoor microclimate. This positioning does not establish the full research intent of church-related studies; rather, it indicates that, within the analyzed keyword network, church research is more strongly connected to energy and conservation-physics terminology than to tourism-management terminology. The result is therefore treated as a bibliometric signal that requires confirmation through systematic content analysis. Equation (2) is used only as a physical interpretation of why visitor occupancy could provide a meaningful bridge between these otherwise weakly connected themes; the equation does not validate the bibliometric inference. The cumulative development of the most frequent keyword terms

over time is presented in Figure 10, providing a temporal complement to the cross-sectional co-word network.

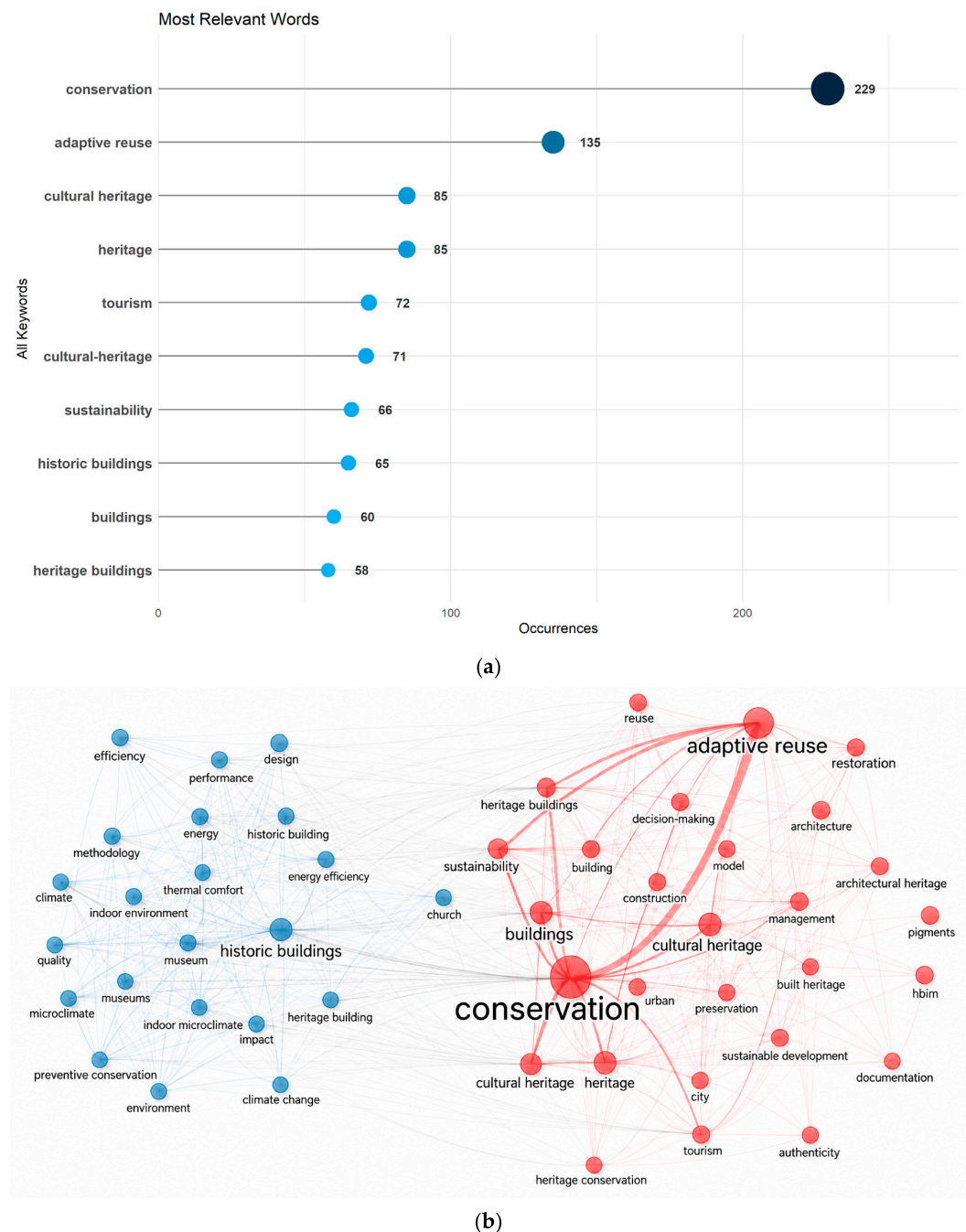


Figure 9. (a) Top 10 keyword terms in the study corpus. The most prominent conceptual anchors are ‘conservation’ ($n = 229$) and ‘adaptive reuse’ ($n = 135$). (b) Keyword co-occurrence network (association-strength normalization, minimum occurrences = 3). Red cluster: heritage management and sustainability concepts (conservation, adaptive reuse, cultural heritage, tourism). Blue cluster: physical building performance concepts (energy efficiency, historic buildings, museum, indoor microclimate, preventive conservation). The explicit worship-typology keyword visible at the selected threshold is ‘church’ (blue cluster); other worship-typology terms are not visible at this threshold, which may reflect their lower frequency in the indexed English-language corpus rather than their exclusion from the research domain. Node size is proportional to keyword frequency; edge thickness reflects co-occurrence strength.

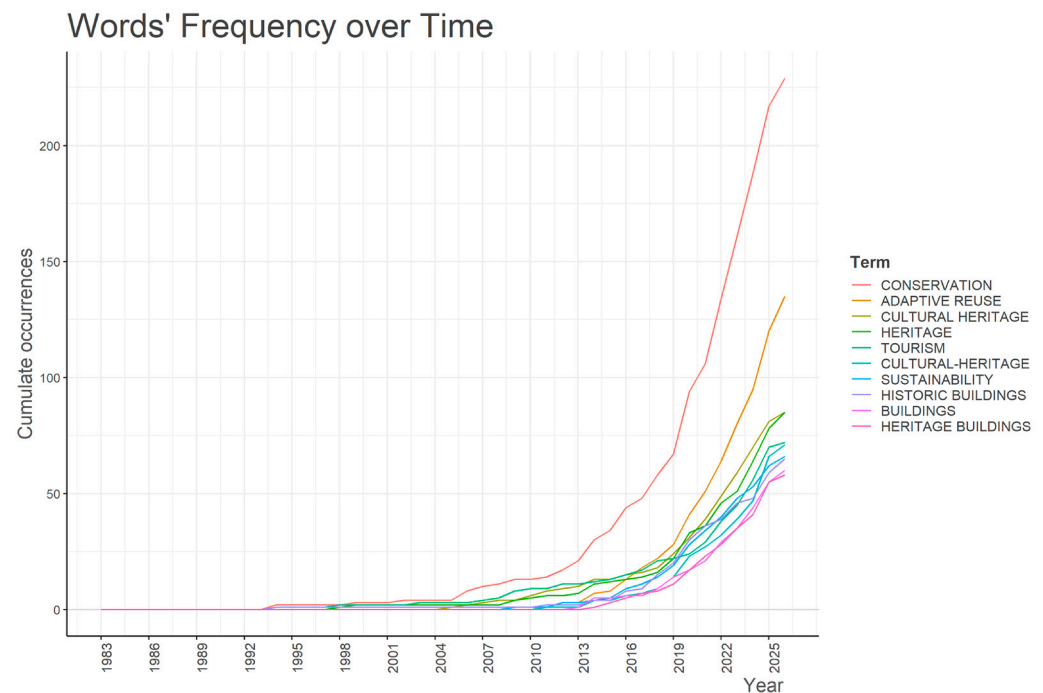


Figure 10. Cumulative frequency of keywords with time (1983–2026). All are driven by conservation. The concepts of adaptive reuse and tourism have experienced particularly rapid development since 2019.

3.8. Thematic Analysis: Strategic Diagram and Trend Topics

The strategic thematic diagram mapped via Callon's density–centrality framework is illustrated in Figure 11, organizing the literature into four technical quadrants:

- **Motor Themes (High Centrality, High Density):** Led by the cluster of 'cultural heritage', 'historic buildings', and 'museum'. The configuration indicates a strongly developed thematic connection between historic-building research and museum-derived microclimate/preventive-conservation concepts; it should not be interpreted as proof that methods have been systematically transferred across all building types.
- **Basic Themes (High Centrality, Low Density):** Composed of 'conservation', 'adaptive reuse', and 'cultural heritage'. The cluster occupies a central but comparatively low-density position, indicating broad relevance with weaker internal cohesion in this network. This pattern is consistent with an interdisciplinary vocabulary that has not yet formed a tightly connected thematic community, but it does not by itself demonstrate the absence of integration in individual studies.
- **Niche Themes (Low Centrality, High Density):** Dominated by the specialized cluster of 'pigments', 'identification', and 'XRF' (X-ray fluorescence). These terms form a dense but peripheral community, indicating strong internal linkage and comparatively weak connection to the broader network. The map does not establish the practical effectiveness or policy relevance of these material-diagnostics methods.
- **Emerging or Declining Themes (Low Centrality, Low Density):** This quadrant includes 'documentation', 'HBIM' (Historic Building Information Modeling), and 'photogrammetry'. The low-centrality/low-density position identifies a weakly developed or changing cluster in the cross-sectional map; by itself, it cannot distinguish emergence from decline. The later bibliographic-coupling and longitudinal thematic-evolution analyses are therefore used to interpret whether HBIM and digital-documentation topics are gaining contemporary prominence.
- **Transitional Theme:** The cluster of 'heritage', 'tourism', and 'management' lies near the center of the density-centrality map. Its position suggests an interdisciplinary interface

with potential to become more structurally central, rather than demonstrating that full integration has already occurred.

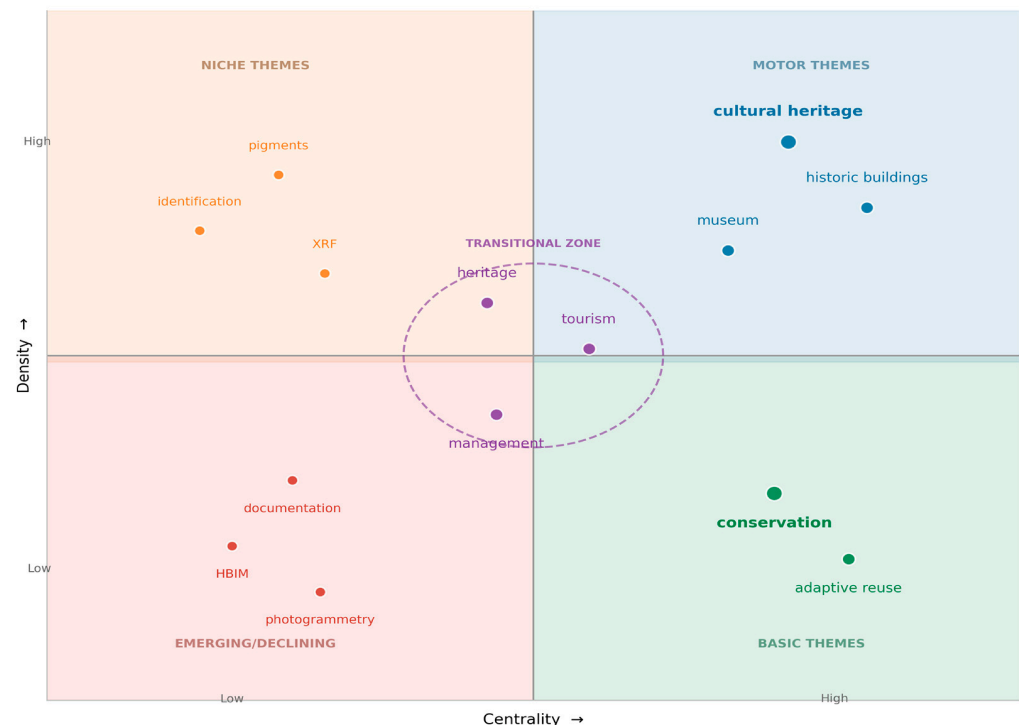


Figure 11. Strategic theme map of Callon’s density-centrality framework. Motor themes (**top right**): museum, historic structures, cultural heritage. Basic themes (**bottom right**): conservation, adaptive reuse, cultural heritage. Niche topics (**upper left**): pigments, identification, XRF. Emerging/declining themes (**bottom left**): documentation, HBIM, photogrammetry. Cluster (**center**) of transition: tourism, heritage, management.

The chronological distribution of trend topics from 2013 to 2026 is mapped in Figure 12. Foundational anchors such as conservation and sustainability span a wider temporal interval, whereas the terms “urban” and “sustainable tourism” are concentrated in the most recent years. This pattern is consistent with a widening topical emphasis from single-building conservation and performance toward broader urban and tourism-management contexts, but the trend plot alone does not establish a causal shift in the field. The temporal sequence is also distinct across topic groups: earlier technical themes such as particulate matter, paintings, pigments, and methodology are concentrated in earlier intervals, whereas heritage conservation, adaptive reuse, urban, and sustainable tourism shift toward the most recent years.

3.9. Co-Citation Analysis: Multi-Disciplinary Intellectual Schools

The co-citation network depicted in Figure 13 tracks the historical intellectual foundations of the domain, distinguishing two clear schools of thought:

- The European Conservation Microclimate School (Blue Cluster): Anchored by the foundational works of Corgnati [25], Camuffo [26], Silva [27], and associated European Committee standardizations. This Mediterranean engineering tradition focuses on modeling indoor microclimatic dynamics and HVAC interactions based strictly on the boundary conditions of vulnerable historical materials (e.g., masonry decay, fresco desiccation) rather than conventional human comfort indices.
- The Adaptive Reuse and Building Management School (Red Cluster): Anchored by Misirlisoy [9], Douglas [28], Foster [10], Plevoets [29], Bullen [30], and Wang [31]. This

cluster approaches built heritage through adaptive reuse, urban planning, circular-economy, and asset-management perspectives, including the adaptation of historical properties for contemporary socio-cultural and tourism-related uses.

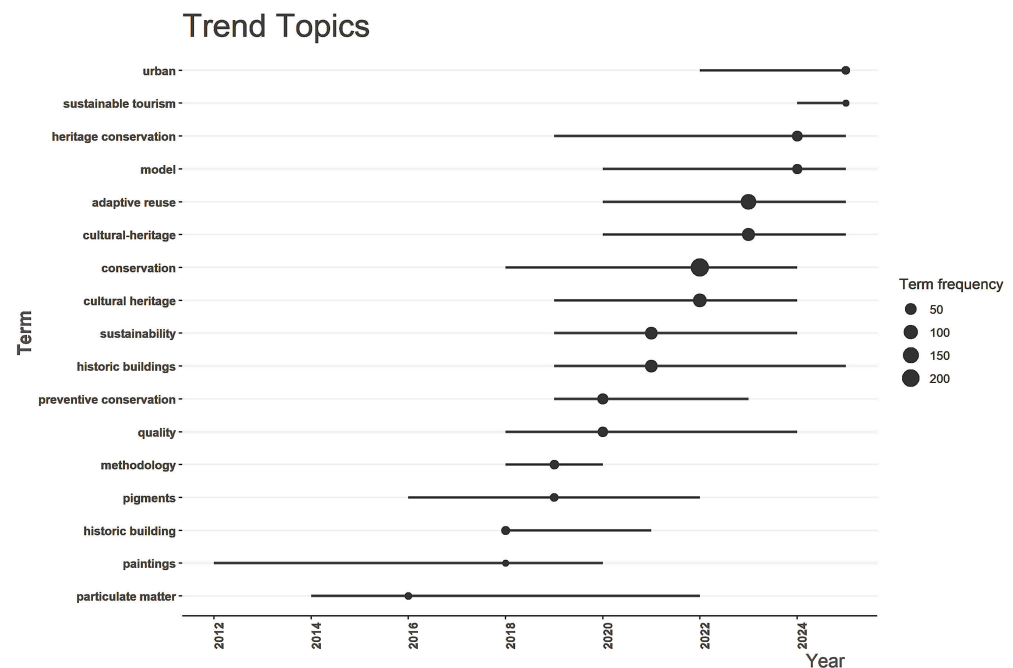


Figure 12. Timeline of trend subjects (2013–2026). Circle size indicates phrase frequency. The last growing research fields are ‘urban’ and ‘sustainable tourism’ (2023–2026).

The structural interface linking these paradigms is mediated by intermediate bridge nodes such as Webb [32] and Martínez-Molina et al. [8]. These nodes indicate partial intellectual overlap between the two schools. The thermodynamic framing introduced in Section 2.2—treating visitor occupancy as a potential operational load—is an interpretive bridge proposed by the authors; it is not a result derived from the co-citation topology itself.

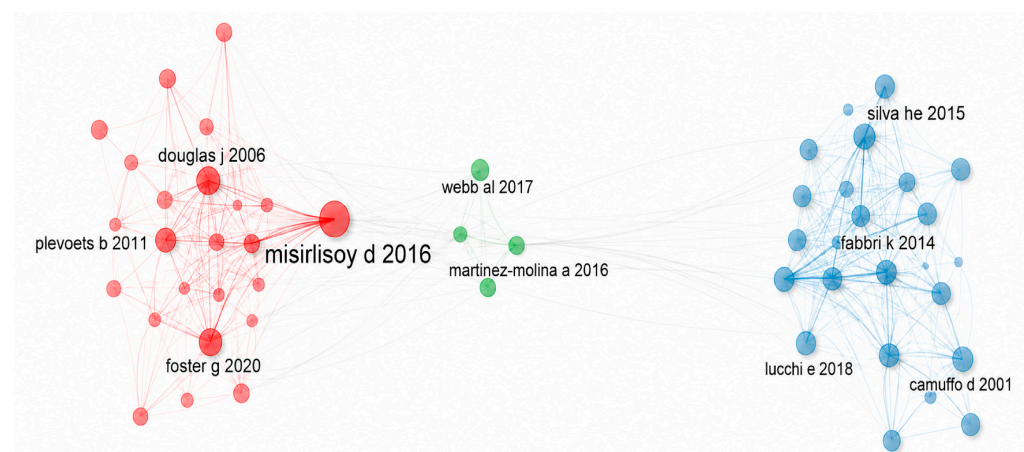


Figure 13. Co-citation network of cited references. Selected anchor nodes in the European conservation–microclimate cluster include Camuffo et al. 2001 [26], Fabbri and Pretelli 2014 [33], Silva and Henriques 2015 [27], and Lucchi 2018 [7]. Selected anchor nodes in the adaptive-reuse/building-management cluster include Misirlisoy and Günçe 2016 [9], Douglas 2006 [28], Foster 2020 [10], and Plevioets and Van Cleempoel 2011 [29]. Martínez-Molina et al. 2016 [8] and Webb 2017 [32] represent bridge nodes. Node size is proportional to citation frequency within the corpus; edge thickness reflects co-citation strength.

3.10. Bibliographic Coupling and Longitudinal Thematic Evolution

Bibliographic coupling provides a complementary, forward-looking view of the field because it connects documents that rely on shared cited references rather than references that are co-cited by later papers. After thresholding, the largest connected backbone contained 328 documents and 2769 links. Louvain clustering produced five communities with modularity $Q = 0.512$ (Figure 14), indicating a meaningful but not absolute separation of contemporary research fronts. The largest community (C1, $n = 172$; mean publication year 2021.6) centers on adaptive reuse, conservation, heritage buildings, cultural heritage, and sustainability. C2 ($n = 114$; mean year 2019.5) concentrates on microclimate, preventive conservation, museum environments, historic buildings, thermal comfort, and energy performance. C3 ($n = 29$; mean year 2023.0) is a newer HBIM/BIM and digital-documentation front. Two smaller fronts capture daylighting and visual-energy optimization (C4, $n = 8$) and spatial-configuration/sustainable-retrofit work (C5, $n = 5$). The five coupling communities and their dominant normalized terms are summarized in Table 3.

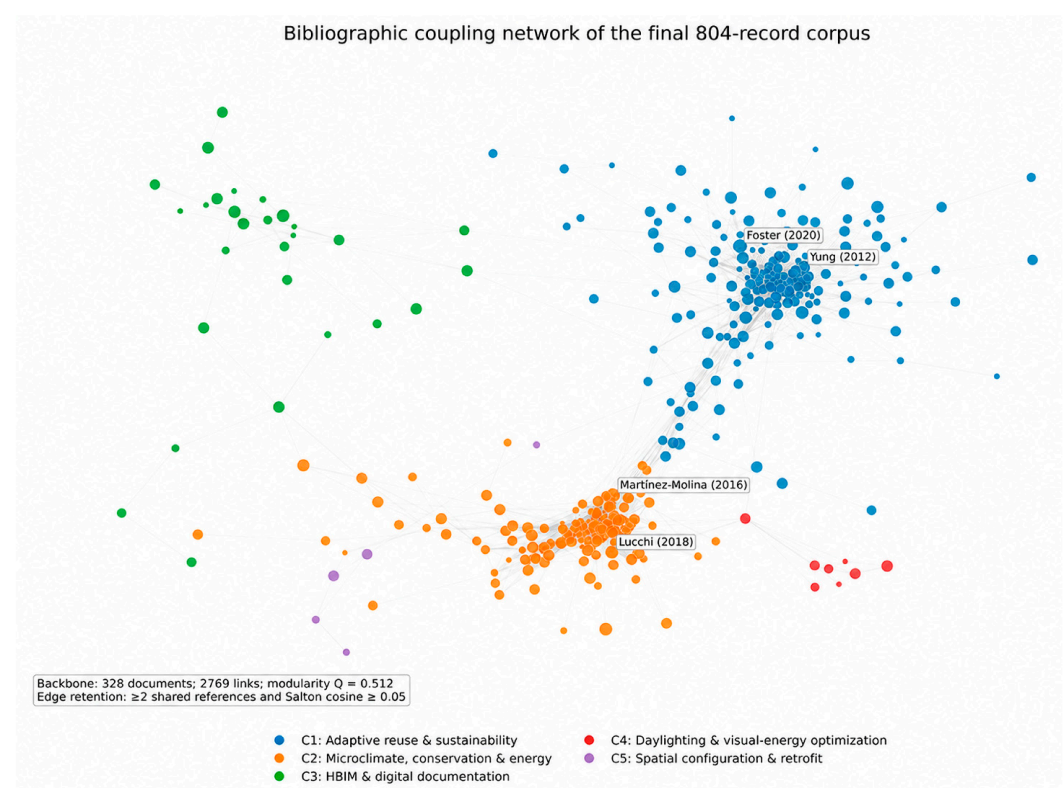


Figure 14. Document-level bibliographic coupling network for the final 804-record corpus. Links were retained when document pairs shared at least two cited references and Salton cosine similarity was ≥ 0.05 . The largest connected backbone contains 328 documents and 2769 links. Node color denotes Louvain community membership (resolution = 0.4; modularity $Q = 0.512$), and node size is scaled by global citations. Representative labeled documents include Foster 2020 [10], Yung and Chan 2012 [4], Martínez-Molina et al. 2016 [8], and Lucchi 2018 [7].

The coupling result refines the earlier co-citation finding. The adaptive-reuse/sustainability and microclimate/conservation-energy fronts remain distinct, but the newer HBIM/digital-documentation community occupies an intermediate methodological space that can support integration across building physics, conservation records, and visitor-use data. This convergence is partial rather than complete: the coupling network still separates management-oriented reuse studies from technical microclimate and energy studies.

Table 3. Contemporary research fronts identified by bibliographic coupling.

Cluster	n (Mean Year)	Dominant Normalized Terms	Interpretive Research Front
C1	172 (2021.6)	adaptive reuse, conservation, heritage buildings, cultural heritage, sustainability	Adaptive reuse & sustainability
C2	114 (2019.5)	conservation, museum, preventive conservation, cultural heritage, historic buildings	Microclimate, conservation & energy
C3	29 (2023.0)	cultural heritage, hbim, bim, documentation, buildings	HBIM & digital documentation
C4	8 (2020.6)	heritage buildings, energy efficiency, comfort, design, historic buildings	Daylighting & visual-energy optimization
C5	5 (2024.6)	space syntax, sustainable retrofit, conservation, spatial configuration, energy retrofits	Spatial configuration & retrofit

Longitudinal thematic evolution provides a second advanced view (Figure 15). The pre-2010 period is sparse, with recurrent themes centered on conservation/tourism/heritage, indoor pollutants, and material diagnostics. Between 2010 and 2018, the literature separates into clearer communities: historic buildings-microclimate-energy, adaptive reuse-cultural heritage-sustainability, conservation-restoration, tourism-management, and XRF/pigment diagnostics. In 2019–2026, these streams consolidate into three larger communities. Tourism and management become embedded within a broad conservation/cultural-heritage community; adaptive reuse joins heritage buildings, historic buildings, sustainability, and energy efficiency; and preventive conservation remains linked to museum and microclimate research. The longitudinal pattern therefore indicates increasing thematic convergence after 2019, but not the collapse of technical and management perspectives into a single research program.

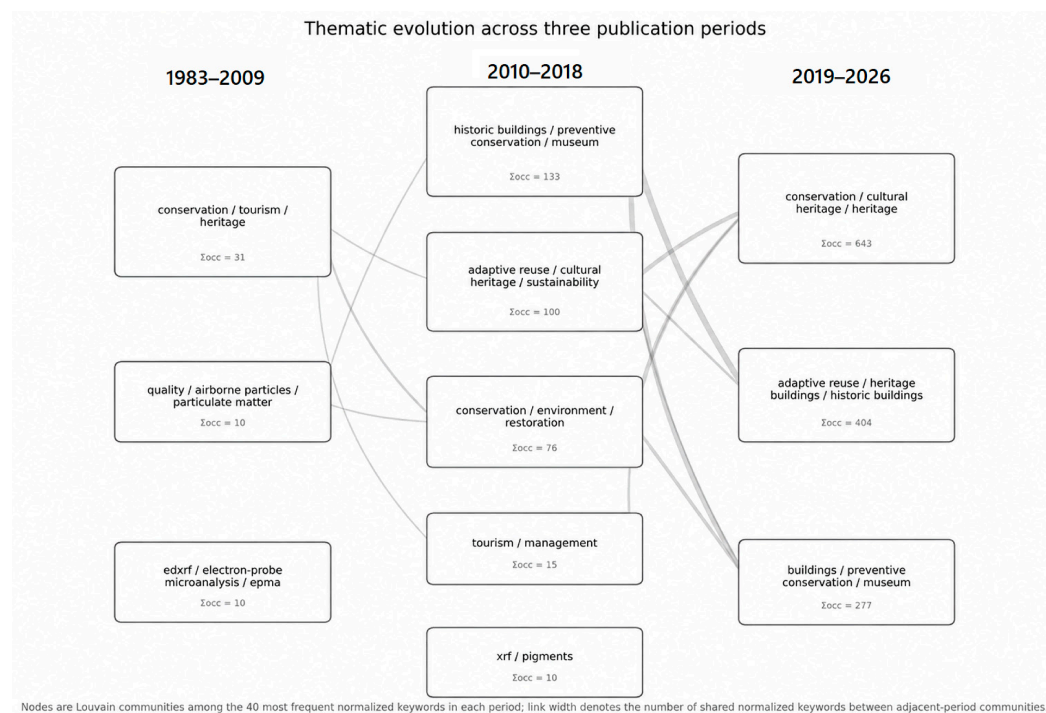


Figure 15. Thematic evolution across 1983–2009, 2010–2018, and 2019–2026. Nodes represent Louvain communities among the 40 most frequent normalized keywords in each period; link width denotes the number of normalized keywords shared by communities in adjacent periods. The figure is intended to show thematic persistence, splitting, and convergence rather than causal transitions.

4. Discussion

4.1. Consolidation Patterns and Strategic Implications for Interdisciplinary Research

The exploratory cumulative-growth fit must be interpreted as a descriptive summary of the observed publication trajectory rather than as direct evidence of lifecycle maturity, saturation, or future deceleration. The current corpus corresponds to 64.9% of the estimated K value; however, this metric is used exclusively as a model parameter within the fitted logistic curve and should not be read as a deterministic saturation threshold. Because the 2025–2026 indexing window remains incomplete, the model does not provide a reliable basis for forecasting future publication volume. In this respect, the cumulative-growth analysis is most useful as an interpretive bibliometric device that contextualizes the rapid increase in publication output after 2019, rather than as a predictive instrument of the field's future trajectory.

Nevertheless, the observed publication growth, the concentration of output in a relatively small set of core journals, and the thematic organization revealed by the science-mapping results suggest that the field is entering a phase in which synthesis, methodological integration, and gap identification are becoming increasingly important. This does not mean that the field has reached a terminal or declining stage. Rather, it indicates that the literature has accumulated enough volume and thematic diversity to support more integrative research designs. In this context, incremental additions to established single-case or single-discipline studies may provide diminishing conceptual returns unless they are connected to broader interdisciplinary frameworks.

The strategic implication is that future research should move beyond isolated case studies and address the structural gap identified in this study: the limited integration of energy engineering, conservation science, and heritage-tourism management. The field may therefore be better served by synthesis articles, comparative empirical studies, HBIM-supported decision frameworks, and monitoring-based research designs that combine building-energy analysis, material conservation requirements, and visitor-use patterns within the same analytical structure. Such approaches would allow the literature to move from parallel disciplinary development toward a more coherent interdisciplinary research agenda.

The added bibliographic-coupling and thematic-evolution analyses strengthen this interpretation without relying on a single keyword map. Coupling separates a management-oriented adaptive-reuse/sustainability front from a technical microclimate/conservation-energy front, while identifying HBIM/digital documentation as a newer research community with bridging potential. The longitudinal analysis further shows that tourism and management become more closely embedded with conservation and cultural-heritage themes after 2019, although technical energy and microclimate streams remain partly distinct. The integration agenda is therefore supported by convergent structural evidence from co-word, co-citation, coupling, and temporal-evolution analyses, while still being framed as a research priority rather than a demonstrated causal mechanism.

Moving from the identification of these gaps to their resolution requires specifying how integration should actually be achieved. At the technological level, Historic Building Information Modeling (HBIM) platforms represent the most tractable integrating infrastructure: they can host energy simulation models, conservation-monitoring records, and visitor flow data within a common spatial framework, enabling simultaneous assessment of retrofit impacts on energy performance, material integrity, and visitor experience. Coupling HBIM with real-time IoT sensor arrays—measuring temperature, humidity, CO₂, and occupancy—would close the monitoring gap between conservation microclimate science and operational energy management identified by the co-citation analysis. At the governance level, integration requires that energy performance obligations—where applicable

to heritage-listed buildings—be designed collaboratively with conservation authorities, specifying acceptable intervention thresholds that preserve material authenticity while achieving decarbonization targets. UNESCO World Heritage site management plans and ICOMOS conservation guidelines could be extended to mandate baseline energy and microclimate monitoring as a standard reporting requirement, generating the empirical data currently absent from the literature. At the research-organization level, multi-site longitudinal studies spanning different climatic contexts (Mediterranean, continental, oceanic) and building typologies (churches, mosques, temples) would provide the comparative evidence base needed to move beyond case-study fragmentation. Such studies should be designed from the outset as interdisciplinary collaborations, embedding building-physics engineers, conservation scientists, and tourism-management researchers within the same project team rather than producing parallel disciplinary outputs that are only superficially integrated in the conclusion.

4.2. The Conservation-Energy Nexus: From Conflict to Convergence

The co-citation structure is consistent with a conceptual progression from studies emphasizing conservation–energy tensions toward work treating conservation and energy performance as potentially complementary dimensions of sustainable heritage management. The European microclimate school, represented by Corgnati [25] and Camuffo [26], focuses strongly on indoor environmental conditions relevant to preservation, whereas the adaptive-reuse literature represented by Douglas [28], Misirlisoy [9], and Foster [10] emphasizes building management, reuse, and functional transformation. Martínez-Molina et al. [8] and Webb [32] provide bridge literature between conservation science and energy engineering, although the mapping indicates that tourism management remains less tightly connected to this technical interface.

The conservation–energy nexus for stone places of worship presents considerable complexity. The following factors demand a delicate balance between engineering optimization and conservation authenticity: the hygrothermal behavior of large stone walls; the microclimatic needs of frescoes and mosaics; the seasonal variation in occupancy between daily prayer use and mass tourism visitation; and the irreversibility of unwanted interventions. The design of an energy system for an Anatolian Seljuk-period stone mosque that may be used by daily worshippers and guided tourism groups, while also being subject to conservation monitoring by multiple regulatory authorities, requires a synthesis of engineering modeling, conservation science, and visitor management planning that no single discipline can deliver alone. This example illustrates why transient masonry heat transfer and occupancy-related thermal loads provide a useful physical context for interpreting the bibliometric separation between conservation–energy and visitor-management themes; Equations (1) and (2) are not solved for this or any other building in the present study.

4.3. Turkey's Underconnected Research Potential in Stone Heritage Studies

Turkey ranks fourth in publication output but has a very low international co-authorship rate ($MCP \approx 3\%$). The bibliometric evidence supports only the observation that Turkish research in this corpus is less internationally connected than its publication volume might imply; it does not identify the reasons for that pattern. The 2020 status change of Hagia Sophia is mentioned solely as an illustrative heritage-management context in which conservation, visitor management, sacred use, and public policy intersect, and it is not treated as empirical evidence for the collaboration result.

Accordingly, international partnership building should be read as a prospective research strategy rather than as a remedy for a demonstrated causal barrier. Joint projects involving Turkish heritage institutions, architecture and engineering programs, tourism

researchers, and Mediterranean or European research consortia could increase opportunities for comparative fieldwork and multi-country evidence. Participation in international programs, shared monitoring protocols, and multi-site studies are proposed here as future options; whether funding structures, institutional priorities, language, or other factors actually explain the observed MCP pattern would require separate survey, interview, or policy-level research.

4.4. HBIM and GIS as Integrating Spatial Platforms

In the strategic map, Historic Building Information Modeling (HBIM) occupies the low-centrality/low-density quadrant, which by itself cannot distinguish emergence from decline. The added bibliographic-coupling analysis, however, identifies a relatively recent HBIM/digital-documentation community (C3; mean publication year 2023.0), supporting its interpretation here as an emerging rather than declining research front. HBIM therefore represents one plausible integrating platform for combining structural geometry, material attributes, thermal-performance data, visitor-flow information, and conservation-monitoring records [34]. The concurrent rise in the term “urban” in Figure 12 is consistent with growing attention to spatial and urban-scale heritage-management questions. Future work could connect building-level HBIM studies with spatial frameworks extending from individual structures to historic districts.

The practical question addressed by this study is how historic places of worship can pursue energy efficiency while maintaining conservation requirements and accommodating heritage-tourism use. HBIM can support building-level performance modeling, while spatial analytical tools can support site-level visitor-flow analysis. In future empirical applications, heritage managers could use such integrated decision support to compare how alternative visitor-management and retrofit scenarios affect indoor microclimate, energy demand, material-conservation conditions, and visitor use. These potential applications require site-specific validation and are not established by the bibliometric analysis itself.

Predictive computational models do not emerge as a dominant cluster in the present bibliometric results, but they represent a plausible future extension of HBIM- and sensor-based conservation management. In structures with episodic mass occupancy, future empirical studies could test whether data-driven occupancy forecasts improve microclimate control while respecting material-vulnerability constraints. This possibility is proposed as a research agenda rather than as a bibliometrically demonstrated trend.

4.5. The Circular Economy and Decarbonization Framing: Built Heritage as Climate Action

Foster [10] is the most globally cited document in the analyzed corpus, with 365 citations, and anchors the circular-economy strand of the literature. From this perspective, adaptive reuse can be interpreted as conserving existing material stocks and potentially avoiding some demolition and reconstruction impacts. The present bibliometric study does not quantify embodied-carbon savings or demonstrate that every restoration intervention reduces life-cycle emissions. For stone places of worship, the relevant empirical question is therefore how conservation-compatible reuse and retrofit strategies affect both embodied and operational impacts under site-specific constraints.

The tourism–conservation–energy linkage should likewise be treated as a hypothesis for empirical and governance research rather than as an outcome demonstrated by the mapping. Heritage visitation may contribute to conservation financing in some contexts, while digital interpretation may supplement physical access, but the magnitude and direction of these effects are site-specific. Future studies should test financing models, visitor-flow strategies, digital-access options, operational energy, and conservation outcomes within

the same longitudinal designs. Such evidence would allow the three domains examined here to be integrated without assuming automatic economic or environmental co-benefits.

5. Conclusions

This study presents a bibliometric and science-mapping analysis of 804 Web of Science Core Collection publications (1983–2026) at the intersection of energy-efficient restoration, sustainable conservation, and heritage tourism, with particular implications for stone places of worship. The analyzed dataset should therefore be understood as a broad historic-building and heritage-management corpus from which implications for stone places of worship are derived, rather than as an exhaustive corpus confined exclusively to stone religious buildings. In addition to performance analysis, co-word mapping, co-citation, and collaboration networks, the revised analysis incorporates document-level bibliographic coupling and longitudinal thematic evolution to distinguish historical intellectual foundations from current research fronts and temporal convergence patterns.

The exploratory cumulative-growth fit is retained only as a descriptive summary of the observed publication trajectory and is not used to infer saturation or future output. Lotka's and Bradford's analyses describe author-productivity asymmetry and source concentration, while the added coupling analysis identifies five contemporary research fronts. The two largest fronts remain centered on adaptive reuse/sustainability and microclimate/conservation-energy, whereas HBIM and digital documentation form a newer research community with potential to bridge these domains. Thematic evolution shows increasing post-2019 convergence of tourism/management with conservation and cultural heritage, but continued partial separation from technical energy and microclimate research.

Co-citation analysis identifies two principal historical intellectual schools: the European conservation-microclimate school and the adaptive-reuse/building-management school. Bibliographic coupling provides convergent but more contemporary evidence of this separation and also reveals an emerging HBIM/digital-documentation front. Tourism management is increasingly connected to conservation and cultural-heritage themes in the recent thematic-evolution network, but its integration with technical energy and microclimate research remains incomplete. The evidence therefore supports a picture of partial convergence rather than a fully unified interdisciplinary field.

Three priority research directions emerge from the combined mapping. First, empirical studies should jointly measure visitor or occupancy patterns, building-energy operation, indoor microclimate, and conservation-performance indicators in the same stone places of worship. This priority is supported by the limited bridging observed across the thresholded co-word, co-citation, and coupling structures; it should be treated as a research gap rather than proof that such integration is absent from every individual study. Second, HBIM-based spatial frameworks should connect energy simulation, conservation monitoring, and visitor-impact assessment across building and urban scales, consistent with the emergence of the HBIM/digital-documentation coupling community. Third, comparative multi-country research involving Turkish, Balkan, Mediterranean, and wider international institutions could address the observed collaboration imbalance while generating more transferable evidence across climates and building typologies. These are prospective priorities derived from structural bibliometric patterns, not causal prescriptions established by the present dataset.

This study has several limitations. First, the dataset was limited to the Web of Science Core Collection; therefore, relevant publications indexed only in Scopus, Google Scholar, national databases, books, professional conservation reports, or local-language outlets may have been excluded. Second, the English-language filter may underrepresent research traditions in countries with rich stone religious heritage, including Turkey, Italy, Greece, Spain,

and countries in the Middle East and North Africa. Third, the search strategy was intentionally broad in order to capture the intersection of historic buildings, energy/conservation interventions, and tourism or visitor-related use. Although manual relevance screening was applied after document-type, language, and subject-category filtering to reduce false positives, the final corpus should be understood as a broad historic-building and heritage-management corpus with particular implications for stone places of worship, rather than as an exhaustive corpus exclusively limited to stone religious buildings. Fourth, bibliometric indicators are sensitive to citation age, database coverage, author-keyword practices, and indexing delay; therefore, recent trends, especially for 2025–2026, should be interpreted cautiously. Finally, the analysis captures the structure of the field at the time of data collection and cannot fully anticipate rapid developments in digital heritage technologies, climate policy, or tourism behavior patterns. Future bibliometric updates, particularly once the post-2024 publication cohort has accumulated sufficient citations, will be needed to reassess the field's cumulative growth pattern and thematic evolution. The added bibliographic-coupling and thematic-evolution analyses are also sensitive to reference canonicalization, keyword normalization, threshold choices, and community-detection parameters. Their clusters should therefore be interpreted as reproducible structural summaries of this corpus rather than as exhaustive or causally distinct research categories.

In conclusion, this bibliometric mapping addresses a gap in the literature by examining how energy-efficient restoration, heritage conservation science, and sustainable tourism are structurally connected across the broader historic-building literature and by translating these structural patterns into research implications for stone places of worship. The contribution is not merely descriptive—identifying who publishes most, in which journal, or on which topic—but structural and prospective. Across co-citation, coupling, co-word, and thematic-evolution evidence, the field shows partial convergence alongside persistent separation between management-oriented and technical research fronts. The resulting research agenda emphasizes integrated empirical monitoring, conservation-compatible building-energy analysis, HBIM-supported decision infrastructure, visitor-flow management, and multi-country comparative research. These priorities provide a testable framework for future empirical studies while remaining appropriately bounded by the evidential limits of bibliometric data.

Author Contributions: Conceptualization, L.K.B., M.A.K. and F.Ü.; methodology, L.K.B., M.A.K. and F.Ü.; software, M.A.K. and F.Ü.; validation, L.K.B., M.A.K. and F.Ü.; formal analysis, L.K.B. and M.A.K.; investigation, L.K.B., M.A.K. and F.Ü.; resources, L.K.B., M.A.K. and F.Ü.; data curation, L.K.B. and M.A.K.; writing—original draft preparation, L.K.B., M.A.K. and F.Ü.; writing—review and editing, L.K.B., M.A.K. and F.Ü.; visualization, L.K.B. and M.A.K.; supervision, L.K.B. and M.A.K.; project administration, M.A.K. and F.Ü.; funding acquisition, L.K.B. and M.A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AIC	Akaike Information Criterion
BIC	Bayesian Information Criterion
BIM	Building Information Modeling

GIS	Geographic Information System
HBIM	Historic Building Information Modeling
HVAC	Heating, Ventilation, and Air Conditioning
ICOMOS	International Council on Monuments and Sites
MCP	Multi-Country Publication
RMSE	Root Mean Square Error
RQ	Research Question
WoS	Web of Science
XRF	X-ray fluorescence

References

- Thinley, J.; Chimi, C.; Chettri, N. Spiritual and Spatial Significance of Choedrak Monastery in the Cultural Geography of Bhutan. *Archaeologies* **2021**, *17*, 407–430. [\[CrossRef\]](#)
- UNESCO. *Policy for the Integration of a Sustainable Development Perspective Into the Processes of the World Heritage Convention*; UNESCO World Heritage Centre: Paris, France, 2015.
- Vardopoulos, I. Critical Sustainable Development Factors in the Adaptive Reuse of Urban Industrial Buildings. A Fuzzy DEMATEL Approach. *Sustain. Cities Soc.* **2019**, *50*, 101684. [\[CrossRef\]](#)
- Yung, E.H.K.; Chan, E.H.W. Implementation Challenges to the Adaptive Reuse of Heritage Buildings: Towards the Goals of Sustainable, Low Carbon Cities. *Habitat Int.* **2012**, *36*, 352–361. [\[CrossRef\]](#)
- Šekularac, N.; Ivanović, J.; Čikić-Tovaročić, J. Application of Stone as a Roofing in the Reconstruction and Construction. *J. Civ. Eng. Archit.* **2012**, *6*, 919–924. [\[CrossRef\]](#)
- ICOMOS. Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage. In *Proceedings of the ICOMOS 14th General Assembly, Victoria Falls, Zimbabwe, 27–31 October 2003*; ICOMOS: Paris, France, 2003.
- Lucchi, E. Review of Preventive Conservation in Museum Buildings. *J. Cult. Herit.* **2018**, *29*, 180–193. [\[CrossRef\]](#)
- Martínez-Molina, A.; Tort-Ausina, I.; Cho, S.; Vivancos, J.L. Energy Efficiency and Thermal Comfort in Historic Buildings: A Review. *Renew. Sustain. Energy Rev.* **2016**, *61*, 70–85. [\[CrossRef\]](#)
- Misirlisoy, D.; Günçe, K. Adaptive Reuse Strategies for Heritage Buildings: A Holistic Approach. *Sustain. Cities Soc.* **2016**, *26*, 91–98. [\[CrossRef\]](#)
- Foster, G. Circular Economy Strategies for Adaptive Reuse of Cultural Heritage Buildings to Reduce Environmental Impacts. *Resour. Conserv. Recycl.* **2020**, *152*, 104507. [\[CrossRef\]](#)
- Aria, M.; Cuccurullo, C. Bibliometrix: An R-Tool for Comprehensive Science Mapping Analysis. *J. Inf.* **2017**, *11*, 959–975. [\[CrossRef\]](#)
- Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to Conduct a Bibliometric Analysis: An Overview and Guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [\[CrossRef\]](#)
- Zupic, I.; Čater, T. Bibliometric Methods in Management and Organization. *Organ. Res. Methods* **2015**, *18*, 429–472. [\[CrossRef\]](#)
- Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [\[CrossRef\]](#) [\[PubMed\]](#)
- Lotka, A.J. The Frequency Distribution of Scientific Productivity. *J. Wash. Acad. Sci.* **1926**, *16*, 317–323.
- Bradford, S.C. Classic paper: Sources of information on specific subjects. *Collect. Manag.* **1976**, *1*, 95–104. [\[CrossRef\]](#)
- Callon, M.; Courtial, J.P.; Laville, F. Co-word analysis as a tool for describing the network of interactions between basic and technological research: The case of polymer chemistry. *Scientometrics* **1991**, *22*, 155–205. [\[CrossRef\]](#)
- Cobo, M.J.; López-Herrera, A.G.; Herrera-Viedma, E.; Herrera, F. Science mapping software tools: Review, analysis, and cooperative study among tools. *J. Am. Soc. Inf. Sci. Technol.* **2011**, *62*, 1382–1402. [\[CrossRef\]](#)
- Van Eck, N.J.; Waltman, L. How to Normalize Co-Occurrence Data? An Analysis of Some Well-Known Similarity Measures. *J. Am. Soc. Inf. Sci. Technol.* **2009**, *60*, 1635–1651. [\[CrossRef\]](#)
- Kessler, M.M. Bibliographic Coupling between Scientific Papers. *Am. Doc.* **1963**, *14*, 10–25. [\[CrossRef\]](#)
- Eijgelaar, E.; Thaper, C.; Peeters, P. Antarctic cruise tourism: The paradoxes of ambassadorship, “last chance tourism” and greenhouse gas emissions. *J. Sustain. Tour.* **2010**, *18*, 337–354. [\[CrossRef\]](#)
- Roberti, F.; Oberegger, U.F.; Lucchi, E.; Troi, A. Energy Retrofit and Conservation of a Historic Building Using Multi-Objective Optimization and an Analytic Hierarchy Process. *Energy Build.* **2017**, *138*, 1–10. [\[CrossRef\]](#)
- Ouellette, P.; Kaplan, R.; Kaplan, S. The Monastery as a Restorative Environment. *J. Environ. Psychol.* **2005**, *25*, 175–188. [\[CrossRef\]](#)
- Pope, G.A.; Meierding, T.C.; Paradise, T.R. Geomorphology’s Role in the Study of Weathering of Cultural Stone. *Geomorphology* **2002**, *47*, 211–225. [\[CrossRef\]](#)

25. Corgnati, S.P.; Filippi, M. Assessment of Thermo-Hygrometric Quality in Museums: Method and In-Field Application to the Duccio di Buoninsegna Exhibition at Santa Maria della Scala. *J. Cult. Herit.* **2010**, *11*, 345–349. [[CrossRef](#)]
26. Camuffo, D.; Van Grieken, R.; Busse, H.-J.; Sturaro, G.; Valentino, A.; Bernardi, A.; Blades, N.; Shooter, D.; Gysels, K.; Deutsch, F.; et al. Environmental monitoring in four European museums. *Atmos. Environ.* **2001**, *35*, S127–S140. [[CrossRef](#)]
27. Silva, H.E.; Henriques, F.M.A. Preventive conservation of historic buildings in temperate climates. The importance of a risk-based analysis on the decision-making process. *Energy Build.* **2015**, *107*, 26–36. [[CrossRef](#)]
28. Douglas, J. *Building Adaptation*, 2nd ed.; Routledge: London, UK, 2006. [[CrossRef](#)]
29. Plevoets, B.; Van Cleempoel, K. Adaptive Reuse as a Strategy towards Conservation of Cultural Heritage: A Literature Review. *WIT Trans. Built Environ.* **2011**, *118*, 155–164. [[CrossRef](#)]
30. Bullen, P.A.; Love, P.E.D. Residential Regeneration and Adaptive Reuse: Learning from the Experiences of Los Angeles. *Struct. Surv.* **2009**, *27*, 351–360. [[CrossRef](#)]
31. Wang, H.J.; Zeng, Z.T. A Multi-Objective Decision-Making Process for Reuse Selection of Historic Buildings. *Expert Syst. Appl.* **2010**, *37*, 1241–1249. [[CrossRef](#)]
32. Webb, A.L. Energy Retrofits in Historic and Traditional Buildings: A Review of Problems and Methods. *Renew. Sustain. Energy Rev.* **2017**, *77*, 748–759. [[CrossRef](#)]
33. Fabbri, K.; Pretelli, M. Heritage Buildings and Historic Microclimate without HVAC Technology: Malatestiana Library in Cesena, Italy, UNESCO Memory of the World. *Energy Build.* **2014**, *76*, 15–31. [[CrossRef](#)]
34. Salvador-García, E.; García Valdecabres, J.L.; Viñals Blasco, M.J. Integrating HBIM Models in the Management of the Public Use of Heritage Buildings. *Can. J. Civ. Eng.* **2019**, *47*, 228–235. [[CrossRef](#)]

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