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TOWARDS INTEGRATED RISK IDENTIFICATION APPROACHES OF PREVENTIVE CONSERVATION FOR ARCHITECTURAL HERITAGE OF TRADITIONAL VILLAGES: A SYSTEMATIC REVIEW

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Abstract

Risk identification in preventive conservation (RIPC) has been successfully implemented across many important architectural heritage sites; however, architectural heritage in traditional villages (AHTV) has received limited attention. Existing RIPC strategies are also difficult to replicate in AHTV due to constraints such as limited resources and spatial complexity. To address this gap, this study followed the PRISMA guidelines to retrieve and screen relevant literature from the Web of Science and Scopus databases. The applicability of RIPC approaches was analyzed across four dimensions: risk types, adaptability to the working environment, costs, and operational simplicity. The results indicate that RIPC approaches differ across these dimensions but are complementary; none performs well across all dimensions, making it difficult for a single pathway to fully meet the requirements of AHTV. Based on the above findings, this review proposes a phased conceptual framework to integrate these RIPC approaches. It involves conducting initial risk screening using cost-effective tools to identify potential risks, followed by in-depth diagnostics employing high-precision approaches. This conceptual framework balances the strengths and limitations of these approaches, providing guidance for the preventive conservation of AHTV.

Keywords: *Preventive Conservation; Risk Identification; Traditional Villages; Architectural heritage; PRISMA*

Introduction

Architectural heritage in traditional villages (AHTV) covers diverse historical building types such as ancient dwellings, ancestral halls, temples, and fortified walls [1], [2], [3]. These elements reflect the regional cultural characteristics and social structures of a specific historical period and constitute non-renewable resources [4], [5]. Current conservation practices for AHTV are mostly reactive, often initiated only after risks have already caused damage [5], [6], [7]. Without a forward-looking strategy, the historical and cultural information embedded in village spaces becomes increasingly vulnerable to irreversible loss [8], [9]. In addition, existing conservation measures have not substantially improved conditions in several traditional villages, which continue to face physical deterioration and external threats [10], [11], [12].

In recent years, preventive conservation has received increasing attention within the heritage conservation community, with growing recognition that proactive intervention is better than curative actions [13], [14]. According to the definition by ICOM-CC, preventive

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conservation comprises all actions taken to avoid or reduce future deterioration or loss [15]. It emphasizes the identification of potential threats before visible damage occurs, relying on cyclical planning [14], [16]. In this process, risk identification in preventive conservation (RIPC), as a critical initial phase, often adopts non-contact or low-invasive approaches to accurately identify potential threats to heritage [17], [18]. Its effectiveness has been validated at many architectural heritage sites [19-22]. For example, De Fino [23] applied photogrammetry with SfM-MVS to generate high-resolution 3D models, enabling the identification of surface defects on architectural heritage. Similarly, He *et al.* [24] found that moisture is a key factor driving the expansion or contraction of cracks in timber-frame buildings through continuous environmental monitoring. These studies indicate that RIPC supports preventive conservation decisions and helps mitigate deterioration, reducing costly repairs [16]. Therefore, introducing RIPC can strengthen proactive conservation of AHTV and extend the lifecycle of heritage.

Compared with these advances, existing studies on AHTV have mainly focused on regional characteristics, restoration, curative conservation, and utilization, with limited systematic exploration of RIPC [25-28]. Although research on risk identification for architectural heritage has developed a range of technical approaches, it has commonly centered on individual buildings or significant heritage sites, and some studies have addressed only a single type or a limited range of deterioration [14], [22], [24]. By contrast, AHTV involves numerous and diverse conservation objects at the settlement scale and is exposed to multiple types of risk. These differences in scale and risk complexity suggest that existing approaches may not be directly transferable to traditional villages [6], [30]. The application of these approaches is further constrained by practical implementation conditions. Digital technologies have become increasingly important for architectural heritage risk identification [19], [20], [24]. However, some digital approaches require sustained financial investment, specialized expertise, and long-term capacity for operation and maintenance. Limited conservation funding and shortages of professional personnel remain common constraints in many traditional villages [8], [30], [31]. Few studies have examined which RIPC approaches are suitable for traditional villages with numerous conservation objects, diverse risks, and limited resources, or how these approaches can be selected and combined to support the preventive conservation of AHTV.

In response to these gaps, this paper adopts a systematic review to examine the empirical evidence from architectural heritage studies and discusses the applicability of the identified approaches to AHTV. On this basis, this study proposes a conceptual framework for risk identification in AHTV to strengthen proactive identification and intervention across multiple risk types. It also provides new perspectives for the conservation of AHTV. The research objectives of this study are as follows:

(1) To summarize trends, thematic distributions, and approaches for risk identification in preventive conservation.

(2) To analyze the applicability of risk identification approaches.

Materials and methods

Systematic review

This study followed the PRISMA guidelines to structure the review process and provide a clear basis for the literature review [33], [34].

Keyword Identification

We first collected terms associated with traditional villages, such as rural areas, historic villages, and historic towns, which are often used interchangeably in research. To improve retrieval, we refined the keywords for AHTV, including architectural types such as traditional courtyard dwellings, religious structures, temples, and public spaces, as well as defensive facilities and other historical environmental elements [31], [35], [36]. Given the limited research on preventive conservation for architectural heritage, we expanded the retrieval scope to include immovable cultural relics. This study also collected keywords related to preventive conservation, including planned preventive conservation, risk preparedness, and Monumentenwacht [37].

Based on these keywords, the search strategy employed in this review is as follows:

(a) Architectural heritage in traditional villages: TS1 = (Traditional villages OR Rural Area OR Historic Town OR Courtyard OR Traditional Courtyard OR Historic building OR Historic Architecture OR Built Heritage OR Religious and Spiritual Space OR Traditional Temple OR Public Space OR Defensive Facilities OR Historic environment elements OR Immovable cultural relic OR Immovable Cultural Heritage)

(b) Preventive conservation: TS2 = (Preventive Conservation OR Planned Preventive Conservation OR Monumentenwacht OR Risk Preparedness)

(c) (TS1) AND (TS2)

The screening procedure

This review searched Web of Science and Scopus databases, with the last retrieval performed on April 20, 2025. The screening process in this study followed the PRISMA guidelines, and inclusion and exclusion criteria were established during the database search (Fig. 1). This study excluded review articles, as their RIPC approaches are not empirically validated and often lack detailed information on procedures and application contexts. To enhance accessibility and reduce retrieval barriers, only English-language and open-access publications were included.

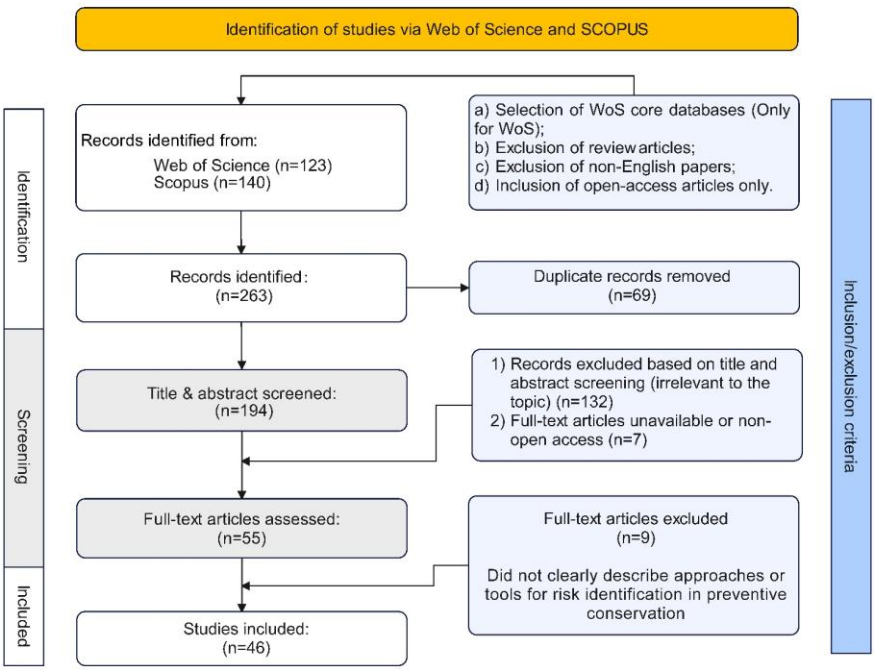


Fig. 1. PRISMA workflow of literature search and review

A total of 263 records were retrieved from the two databases. After removing 69 duplicates, 194 document records remained. Titles and abstracts were screened to exclude studies unrelated to the focus of this review. Also, we excluded preventive conservation in the fields of archaeology, museums, libraries, and archives, as their objectives differ from those of architectural heritage conservation. In these fields, risk identification typically focuses on preserving artifacts, books, documents, and collections. Standard risk identification methods include thermostatic and hygrometric monitoring, microbial analysis, and environmental management systems. After title and abstract screening, 62 articles remained. Seven full-text articles were unavailable or not open access, leaving 55 articles for full-text assessment. We then applied the full-text eligibility criteria (Fig. 1) and excluded any articles that did not meet the criteria. Ultimately, 46 studies met the screening criteria and were included in the results section for analysis of RIPC approaches (Table 1).

Table 1. List of studies included via PRISMA

No.	Focused Heritage Type	Risk Identification Approaches and Tools	Ref.
1	Architectural heritage	1. Periodic inspection (On-site observations, Point-cloud data acquisition and analysis (PCDAA) included) 2. Heritage monitoring	[38]
2	Central Market of Algeciras, Spain	1. Periodic inspection (On-site observations, Visual data acquisition and analysis (VDAA) included)	[39]
3	Church of Santa Ana, Seville	1. Periodic inspection (On-site observations, PCDAA included) 2. Heritage monitoring	[40]
4	San Juan Bautista Church, Nabón	1. Periodic inspection (On-site observations, PCDAA included)	[41]
5	São Torcato church and San Pedro church	1. Periodic inspection (On-site observations, PCDAA included) 2. Heritage monitoring	[42]
6	Monastery of Santa Maria de Salzedas	1. Periodic inspection (On-site observations, VDAA included)	[43]
7	Chapel of Susudel, Ecuador	1. Periodic inspection (On-site observations, PCDAA, VDAA included) 2. Heritage monitoring	[44]
8	Visby, Sweden	1. Periodic inspection (On-site observations, VDAA included)	[45]
9	Architectural heritage in Flanders, Belgium	1. Periodic inspection (On-site observations, VDAA included) 2. Heritage monitoring	[46]
10	Yangjia Courtyard, Nanyang, China	1. Periodic inspection (On-site observations included)	[47]
11	Immovable cultural heritage, Beijing	1. Periodic inspection (On-site observations, PCDAA included) 2. Heritage monitoring	[48]
12	San Domenico Church	1. Periodic inspection (On-site observations, PCDAA included)	[49]
13	Hexia Ancient Town	1. Periodic inspection (VDAA included)	[50]
14	Architectural heritage	1. Periodic inspection (On-site observations included)	[51]
15	San Pietro bell-tower and Torre degli Sciri	1. Heritage monitoring	[52]
16	Karnak Temples, Egypt	1. Periodic inspection (On-site observations, VDAA included) 2. Heritage monitoring	[53]
17	Gongsanseong Fortress	1. Periodic inspection (On-site observations, VDAA included) 2. Heritage monitoring	[54]
18	St. Joseph Chapel in Reims, France	1. Periodic inspection (On-site observations, VDAA included) 2. Heritage monitoring	[55]
19	Forbidden City, Beijing	1. Periodic inspection (On-site observations included) 2. Heritage monitoring	[56]
20	built and natural heritage	1. Heritage monitoring (Sensor Placement)	[57]
21	Real Colegio-Seminario de Corpus Christi	1. Periodic inspection (PCDAA included) 2. Heritage monitoring	[58]
22	Lujiang Academy, Guangzhou	1. Periodic inspection (On-site observations (Testing) included)	[59]
23	Historic assets	1. Heritage monitoring	[60]
24	Valencia (3 Landmark Buildings)	1. Periodic inspection (PCDAA, VDAA included) 2. Heritage monitoring	[61]
25	Lojuela Castle, Spain	1. Periodic inspection (PCDAA, VDAA included)	[62]

No.	Focused Heritage Type	Risk Identification Approaches and Tools	Ref.
26	Architectural heritage, Italy	1. Periodic inspection (On-site observations, VDAA included) 2. Heritage monitoring	[63]
27	Earthen heritage, Iberia	1. Periodic inspection (On-site observations, VDAA included) 2. Heritage monitoring	[64]
28	Cross-Regional Cultural Heritage, Northeast China	1. Periodic inspection (On-site observations included)	[65]
29	Defensive Architecture, Southeast Al-Andalus	1. Periodic inspection (On-site observations, VDAA included)	[66]
30	Vernacular architecture, Yazd	1. Periodic inspection (On-site observations included)	[67]
31	Historical buildings, Shifeng village, Chaozhou	1. Periodic inspection (On-site observations, VDAA included) 2. Heritage monitoring	[68]
32	Churches	1. Periodic inspection (On-site observations included)	[69]
33	Courtyard of the Maidens in the Royal Alcázar of Seville	1. Periodic inspection (On-site observations, VDAA included) 2. Heritage monitoring	[70]
34	Cerrillos Tower, Spain	1. Periodic inspection (On-site observations, PCDAA, VDAA included)	[71]
35	Gabbia tower, Mantua	1. Periodic inspection (On-site observations included) 2. Heritage monitoring	[72]
36	Chinese ancient city towers, the Ming-Xianling Tomb	1. Periodic inspection (On-site observations, PCDAA, VDAA included)	[73]
37	Temple of Resurrection in Jerusalem	1. Periodic inspection (On-site observations included) 2. Heritage monitoring	[74]
38	wooden churches near Krakow	1. Secondary data collection	[75]
39	churches, America (Colombia and Guatemala)	1. Periodic inspection (On-site observations, VDAA included)	[76]
40	Santa Catalina Church, Seville	1. Periodic inspection (On-site observations, VDAA included) 2. Heritage monitoring	[77]
41	Heritage buildings, Costa Rican	1. Periodic inspection (On-site observations, PCDAA, VDAA included)	[78]
42	Main hall of Baoguo Temple, Ningbo	1. Periodic inspection (On-site observations, PCDAA included)	[79]
43	City Theatre, Norrköping	1. Heritage monitoring	[80]
44	Ziri Wall, city of Granada	1. Heritage monitoring	[81]
45	Confucian Temple, Tainan	1. Heritage monitoring	[82]
46	The dome of the Basilica of Santa Maria degli Angeli, Assisi	1. Heritage monitoring	[83]

Indicators for applicability analysis

To address the identified gap, this study developed applicability analysis indicators by integrating the practical challenges of AHTV with relevant research on RIPC in architectural heritage [8], [31], [46]. These indicators were grouped into four core dimensions: identified risk types, adaptability to working environments, operational simplicity, and costs. Risk types are included as indicators because different approaches or tools may vary in the types of risks they are suited to identify. For example, scanning techniques are often applied to structural damage identification, whereas sensor monitoring is commonly used to track changes in heritage and environmental conditions [40], [44].

Accordingly, this study introduces an applicability analysis, structured into several refined indicators to ensure its operability.

Concerning adaptability to working environments, the study examines the data collection capabilities of different methods in large-scale heritage scenarios (because traditional villages often contain numerous heritage assets) and adaptability in complex settings such as narrow alleys and vegetation obstructions [7], [26].

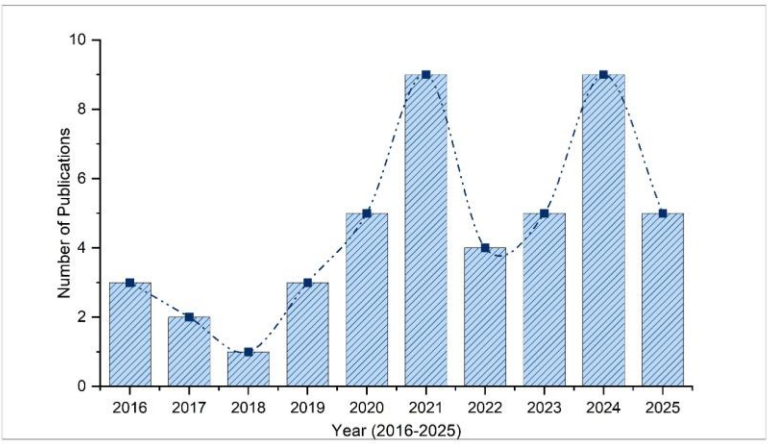
Operational simplicity is assessed in two stages, data collection and risk extraction, based on process complexity, efficiency, and reliance on professionals [41], [43]. Existing research indicates that while some high-precision methods demonstrate outstanding performance in monumental heritage conservation, their application in traditional villages has been limited by operational complexity and high dependence on experts [60], [68].

To assess cost, the study draws on existing descriptions of the RIPC process and distinguishes between data collection and risk extraction to evaluate resource requirements [42], [50], [68].

Results

Research trends and thematic distribution

This study analyzed the 46 selected publications in terms of annual output, types of heritage addressed, and types of risks involved and conducted keyword burst and clustering analysis using CiteSpace. The aim was to identify research trends and thematic distributions in RIPC. As shown in figure 2, the number of publications remained relatively stable between 2016 and 2018 but had higher volatility from 2019 to 2025. Notably, there was an upward trend after 2022. This increase may be linked to advances in digital tools, machine learning, and artificial intelligence, which are applied in RIPC to enhance their efficiency.



Note: Data for 2025 include publications retrieved up to April 20, 2025.

Fig. 2. Trends in the publication of papers

Among the 46 studies included in this review, the targeted heritage types largely align with the core components of AHTV. These include castles, palaces, ancestral halls, temples, churches, ancient defensive facilities, and elements of the historical environment. This research not only identifies common risks in built heritage, such as material deterioration, structural deformation, and biological erosion, but also reveals threats arising from environmental change, human activities, and natural disasters. These types of risks are also widespread in AHTV, where the challenges are often more pronounced due to inadequate protection mechanisms and limited preventive capacity [81], [82].

In this review, 35 studies collected secondary data, aiming to determine the heritage conservation status or to support risk extraction processes [42]. Several studies also indicate that secondary data, such as heritage conservation documents and technical guidelines, can support on-site data collection and risk extraction. In particular, these documents can be used as references to standardize professional terminology and procedures in heritage conservation, reducing discrepancies in heritage information recording among different inspectors [43].

In contrast, on-site data collection strategies constituted the primary data source, with 45 studies employing periodic inspection, monitoring, or both for RIPC. The periodic inspection strategy is a common measure in RIPC. It originated from the daily care of buildings advocated by John Ruskin and William Morris during the mid-nineteenth century [45]. Over time, this model has been successfully promoted in several European countries, such as the Netherlands, Belgium, and the United Kingdom [46]. As shown in Table 1, 38 studies were related to periodic inspections. Among these, 35 relied on on-site observations, 13 employed point-cloud acquisition and analysis (PCDAA), and 21 used visual data acquisition and analysis (VDAA). This indicates that on-site observations remain the most commonly used approach in periodic inspections, while the adoption of PCDAA and VDAA reflects the gradual application of technical methods in RIPC. Meanwhile, 27 studies combined two or more periodic inspection pathways to enhance the accuracy of RIPC. In addition, 26 studies emphasized the importance of monitoring to capture the dynamic changes in the heritage conditions of both structural and environmental aspects. Also, monitoring provides timely risk identification to support preventive conservation decisions, a capability not offered by other approaches.

To further explore thematic distributions in the field of RIPC, we imported the screened bibliographic data into CiteSpace for keyword burst and clustering analysis. The parameters were set as follows: Time Slicing was set to 2016-2025, and Years Per Slice was set to 1. Then, the node type was selected as the keyword, and the default settings for the other parameters were kept. As shown in figure 3, CiteSpace selected the top 20 keywords with the strongest citation bursts. It shows that current research mainly focuses on risk types and risk identification technologies (e.g., sensor networks, digital twins, computational methods, and ambient vibration testing). Keyword clustering similarly reflects attention on risk types (e.g., #0, #1, #4, #9) and optimization of advanced technologies (e.g., #5, #7, #11). Together, these findings reveal a strong technological bias in RIPC, with limited attention to applications in resource-constrained heritage contexts.

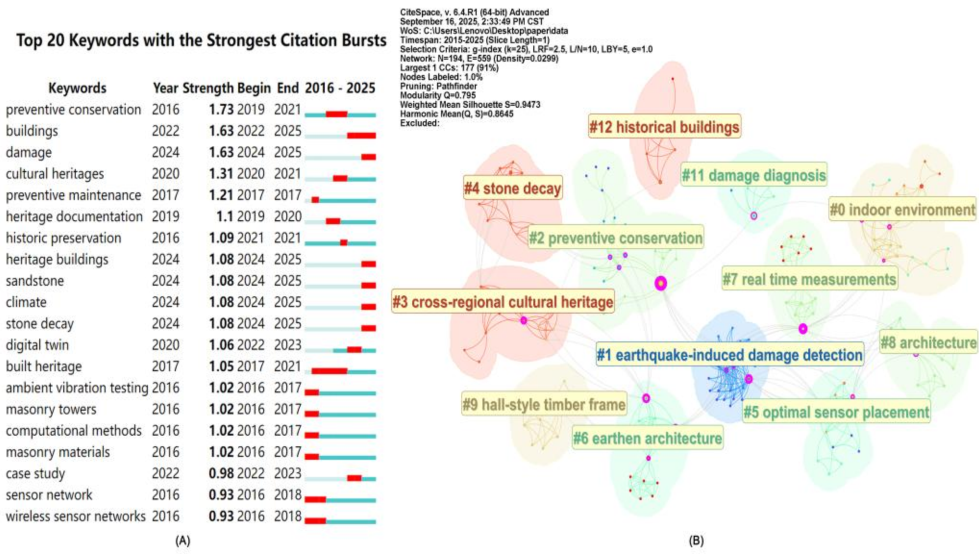


Fig. 3. (A) Top 20 Keywords with the strongest citation bursts; (B) Keyword clustering analysis

Approaches for risk identification

The process of risk identification can be summarized as data collection and risk extraction [44]. This review reveals that the mode of data collection usually dictates the approach to risk extraction. For example, photogrammetry and scanning are often used to analyze point cloud data [48]. At the same time, heritage monitoring often relies on threshold-based judgment or data analysis to identify specific risks [54], [83]. Based on this principle, this review is organized according to different pathways of RIPC, covering both the data acquisition and risk extraction phases.

On-site observations

On-site observations usually rely on experienced judgment to identify visible surface damage and external threats, including deterioration of heritage materials (e.g., weathering, decay, etc.); structural damage (e.g., cracks, deformation, collapse, etc.); environmental erosion (e.g., freeze-thaw damage, bio-erosion, etc.); disaster risks (e.g., floods, droughts, etc.); and human-induced risks (e.g., inappropriate interventions, fire hazards, etc.) [37], [47]. Notably, surface damage covers many common risk types in architectural heritage. Risks that do not originate from the surface layer (e.g., structural displacement, internal material deterioration, or moisture issues) are often reflected on the heritage surface through features such as cracks, discoloration, or deformation [46], [48].

This approach is usually implemented based on the visual and experiential judgment of inspectors [46]. Alternatively, it follows relevant standard documents and guidelines for systematic diagnosis and documentation, which effectively reduces discrepancies in judgment among different inspectors [48]. Certain studies also use sampling tests or experiments for more in-depth risk diagnostics [40]. For instance, Yang *et al.* [47] sampled wooden components from historic buildings to determine the decay level by ATR-FTIR.

This review shows that on-site observations are well-suited for risk identification in complex environments, particularly in narrow areas, dense building clusters, and interior spaces [53], [54]. For large-scale detection, on-site observations are usually combined with UAV-based imaging and other techniques to improve the efficiency of identifying risks [48].

On-site observations are generally easy to implement because their procedures are simple, although further risk assessment may require inspection, testing, or simulation. For example, Wu and van Laar [46] showed that inspectors could conduct risk identification after brief training, under the condition that they followed the manual of the Monumentenwacht model. Furthermore, Yang *et al.* [68] introduced non-specialists into the risk identification process of AHTV, confirming the risks through expert input and partially alleviating the shortage of professionals.

Although existing research has not explicitly addressed the costs associated with on-site observations, the cost of conducting individual heritage inspections using professionals and simple tools generally tends to be manageable [42], [44]. However, as the number of inspection targets increases, personnel requirements, time, and overall costs rise significantly. On-site observations are also less efficient for large-scale risk identification, making it challenging to ensure continuous heritage inspections with limited resources.

Point-cloud data acquisition and analysis

Point-cloud data acquisition and analysis (PCDAA) focuses on capturing the geometric characteristics of architectural heritage to generate point-cloud data for recording, analyzing, and identifying structural changes and surface damage (e.g., cracks, deformations, displacements, fractures, etc.) [44], [79]. In this review, point-cloud data was collected through both scanning and photogrammetry. The advantage of scanning is that it can capture high-precision data at the sub-centimeter to millimeter level, with the capacity to identify minute deformations and complex geometric details [78]. But in densely built-up or confined areas, challenges with setting up the site may lead to partial data gaps [42]. Although portable laser scanners can enhance adaptability for data collection in complex environments, their precision is lower than that of static scanning techniques [42]. Photogrammetry is an alternative approach that offers lower costs and flexible image acquisition, which makes it more adaptable in complex environments. Nevertheless, the accuracy of this approach is generally lower than that of static scanning, and factors such as lighting, angle, and obstruction need to be managed to avoid affecting subsequent data processing [49], [73].

The application of PCDAA has certain limitations regarding operational simplicity and costs. In terms of operational simplicity, deploying scanning tools is complicated, and collecting data requires setting up multiple stations or selecting multiple scanning points [42]. Photogrammetric data collection also requires strict adherence to image overlap requirements for the SfM-MVS algorithm to reliably extract feature points [49]. After data acquisition, point cloud data is generated and must undergo a complex processing workflow (including registration, denoising, and reconstruction) to identify and annotate damage. This process is complex and highly dependent on technical personnel, especially for high-resolution processing, which may result in longer processing times [41]. For example, Masciotta *et al.* [42] reported that two technicians spent three weeks completing the point cloud data processing and subsequent extraction of risk factors for the São Torcato church. As for costs, most studies included in this review employed professional-grade equipment (e.g., Leica RTC360 and Faro Focus X-130) for geometric data collection, which is highly costly, while photogrammetry is a cost-effective method for acquiring data through cameras or UAVs [61], [71], [79]. However, both approaches require complex and time-consuming point-cloud data processing to extract risk information, resulting in higher overall costs [61]. These findings indicate that although PCDAA delivers high-precision data, its practical application is constrained by high costs, reliance on skilled personnel, and long processing times, which must be carefully considered in applicability assessments.

Visual data acquisition and analysis

Visual Data Acquisition and Analysis (VDAA) captures images of architectural heritage and uses empirical judgment or deep learning algorithms to identify visible surface damage (e.g., material deterioration, structural deformation, color changes, erosion, etc.) and external threats (e.g., spatial load-bearing capacity). VDAA shows strong adaptability in diverse environments. Its flexible selection of data collection tools (e.g., cameras, UAVs, mobile phones) for different scenarios enables it to handle data collection tasks across various scales and complex environments. UAVs in particular are highly efficient for large-scale data collection.

The advantages of VDAA include its low cost and ease of operation during the data collection phase. Most studies collect visual data using consumer-grade devices, such as UAVs, cameras, and smartphones. This approach provides a simple image acquisition process without the need to consider overlapping images, as is typical in photogrammetry. As demonstrated in the study by Yang *et al.* [68], even villagers can participate in collecting visual information. However, visual data are vulnerable to lighting conditions, shooting angles, and resolution issues, all of which may affect subsequent analysis. Zhang *et al.* [50] indicated that acquiring multi-temporal, multi-angle data is an effective way to mitigate such interference. During the risk extraction phase, there are differences in operational simplicity between manual experience-based judgement and deep learning, both of which require a highly skilled workforce. For example, manual experience-based judgment involves researchers or experts interpreting images according to classification guidelines (e.g., the Damage Atlas, Project HeritageCare standards), providing a simple workflow [40], [45], [62]. Nevertheless, manual analysis requires more personnel and time as data volume increases, resulting in higher costs and posing challenges in contexts where professionals are scarce and efficient analysis is required [55]. In this context, deep learning-based image analysis has been validated for the efficient extraction of risks in batch processing. In this review, two technical approaches involving supervised and semi-supervised learning are used for deep learning-based image analysis. Supervised learning is trained using damaged sample datasets. It has the advantage of automatically batch-processing the extraction of damage types or locations [61]. The latter approach learns only from non-damaged samples and aims to reduce the pressure of manual annotation and the computational load [50]. Similarly, implementing deep learning algorithms involves higher costs, complex processes, and heavy reliance on specialized expertise, particularly for supervised learning approaches, which rely on dedicated training datasets.

While VDAA shows potential for identifying risks in a highly effective and batch-processed manner, its ability is limited to recognizing risk types and marking their locations [45]. This limitation implies that further analysis and confirmation are required to obtain specific damage information, which necessitates integration with other approaches.

Heritage monitoring

This review found that over half of the studies used monitoring technologies to track changes in architectural heritage [52], [53]. Monitoring indicators cover structural conditions (e.g., deformation, displacement, vibration, etc.), environmental factors (e.g., temperature and humidity), and meteorological parameters (e.g., wind direction, precipitation, etc.) [38], [74], [77]. For instance, Park *et al.* [54] conducted SHM on the Gongsanseong fortress in Gongju, South Korea, which included deformation, displacement, slope, and information on surrounding environments such as temperature and wind direction. Relevant studies have also revealed that heritage monitoring has the potential to acquire continuous data under complex environmental conditions [64], [72]. This capability relies on sensor networks for data collection, which enable operation inside and outside buildings and in open or structurally complex architectural spaces [82], [83]. Nevertheless, this advantage is often limited in practice due to constraints such as power supply, communication quality, and sensor coverage range [57], [58].

Regarding operational simplicity, although data can be acquired automatically through sensor networks, deploying the sensors is a complex process that requires specialized personnel [57], [58], [83]. The accuracy of the data is also directly impacted by the selection of sensor locations and quantities [43]. Two approaches are used in the risk extraction process in heritage monitoring. The first approach involves capturing data that exceeds threshold ranges to identify potential risks [54]. Another method identifies potential risks and their causes by analyzing time-series data [56]. Both approaches are employed in constructing digital twin platforms, which can quickly reflect and analyze abnormal conditions in heritage structures and environments [60]. While these approaches are effective at locating damaged areas and identifying causes, they rely on specialized personnel and involve complex software processing with iterative threshold adjustments, resulting in operational limitations.

Meanwhile, implementing heritage monitoring has higher costs during the data collection phase because factors such as the scale of the buildings, the number of sensors, and monitoring indicators contribute to the overall cost [63]. Relevant studies have not addressed the costs associated with the risk extraction phase of monitoring systems. Compared to the high upfront investments required during installation and maintenance, expenses associated with risk extraction are often hidden in reliance on specialized personnel and software. In this review, monitoring has mainly been applied to architectural heritage with significant value, which benefits from relatively sufficient financial budgets; also, many of these properties have already been exposed to risks or are located in disaster-prone zones. Therefore, the application of monitoring methods should be carefully considered in light of the specific conditions of each site.

Applicability analysis for risk identification approaches in preventive conservation

This study analyzes different RIPC approaches based on dimensions of risk types identified, adaptability to the working environment, costs, and operational simplicity. Building on this review, this study develops an analytical framework (Table 2) designed to compare the application potential of different approaches in AHTV conservation, thereby guiding preventive conservation practices.

The results indicate that on-site observations and VDAA perform better at identifying risk types, especially on-site observations, which are good at identifying unstructured risks (e.g., improper usage and facility aging). VDAA is effective at quickly detecting surface damage and other risks, but it requires additional approaches for confirmation and quantification. In contrast, PCDAA offers high-precision damage information. At the same time, monitoring enables the timely tracking of structural and environmental changes in properties. However, both approaches have limited capability in identifying risk types.

Table 2. Applicability analysis framework for RIPC approaches

Approach	Risk types identified	Adaptability to the working environment	Costs	Operational Simplicity
On-site observations	a) Surface damage and structural deterioration b) External threats (e.g., improper use, etc.)	a) Mainly for small to medium sites; less efficient for large-scale risk identification. b) Covers exterior, interior, and structure; adaptable to complex settings.	Cost depends on the number of professionals and inspection items and increases significantly with workload.	Simple process. It has lower efficiency and relies on the judgment of professionals.
VDAA	a) Surface damage b) External threats (e.g., carrying capacity, etc.)	a) Data collection can be performed at different spatial scales. b) Performs better in open/poor-access areas.	a) VDAA has lower data-collection costs. b) Deep learning models require a high initial cost for setup.	a) Simple process and higher efficiency in data collection, but requires precise image data. b) Deep learning-based VDAA is more efficient but requires a complex setup and professional expertise.
PCDAA	Changes in the structure, surface texture, and geometric information of the heritage	a) Scanning and photogrammetry are commonly applied for data collection on individual heritage assets. b) PCDAA may be limited in narrow spaces or dense areas.	a) Scanning requires costly professional equipment; photogrammetry can use consumer-grade devices. b) Data processing and analysis are time-consuming and costly.	a) Photogrammetry has a more straightforward data collection process than scanning. b) Data processing requires point-cloud stitching and modeling, which is complex and relies on professionals.
Heritage monitoring	Dynamic changes in structure and environment	a) Monitoring is often applied to small-to-medium-sized heritage sites or individual heritage properties. b) Unrestricted in complex spaces but influenced by factors such as communication and power supply.	Higher cost for sensor installation, operation, and maintenance.	a) The sensor deployment process is complex. b) Data processing for monitoring relies on professionals.

Regarding adaptability to working environments, VDAA, on-site observations, and monitoring generally perform well in complex settings, though there are limitations to consider for each. Specifically, VDAA faces challenges with image clarity, lighting, angle, and object occlusion. Monitoring provides continuous data recording and transmission, depending on stable power and communication systems. In contrast, PCDAA is poorly suited to complex environments because its data collection depends heavily on specific procedures and site conditions. There are strict requirements for scanning angles, visibility, and station placement, which often result in data gaps in dense or obstructed areas. Photogrammetry and portable scanners can partially solve this problem, but typically at the expense of data accuracy. For large-scale data collection, VDAA relies on UAVs to capture wide-area information. Although PCDAA can also use UAVs to obtain point cloud data, the lengthy and complex process of extracting risks limits its large-scale application. High costs restrict monitoring, making it difficult to apply on a large scale in architectural heritage. Similar challenges exist for on-site observations, as their efficiency depends heavily on the number and expertise of professionals [46]. Some studies suggest involving villagers to ease the shortage of experts, but this approach requires long-term community engagement and training [68].

In terms of cost and operational simplicity, on-site observations involve relatively straightforward procedures. However, they require specialized personnel to perform this process, and the cost increases linearly as the scale of the inspection increases. PCDAA and monitoring are more complex in data collection and risk extraction, requiring high costs for specialized equipment and technical support. VDAA offers simpler, cost-effective data collection. However, developing deep learning–based VDAA models is complicated and requires specialized technical support, resulting in higher initial investment and support costs. The model can be reused across many traditional villages within a region, which greatly reduces the cost per individual risk identification.

The analysis indicates that existing approaches for RIPC differ in these four dimensions, with no single approach meeting all dimensions. Also, the characteristics of these approaches and tools show a complementary relationship. For instance, VDAA is well-suited to fast screening but is unable to quantify damage. Conversely, on-site observations, PCDAA, and monitoring provide more precise diagnostics, compensating for the limitations of VDAA while enhancing their own efficiency. At the same time, combining these approaches can reduce the overall cost of identifying risks, improve operational simplicity, and reduce reliance on specialists. These differences and complementary aspects reveal the potential for integrating these approaches and provide a foundation for proposing a multi-stage pathway for RIPC.

Discussion

Based on a systematic review, this study found that current research on RIPC approaches generally shows a trend toward digitalization and high precision. In contrast, this study argues that RIPC for traditional villages should give full consideration to the constraints imposed by their actual conditions. The applicability analysis further revealed the distinct characteristics and limitations of different pathways in village contexts, with complementarity among these approaches. The results also indicated that effective RIPC for AHTV relies not on a single pathway, but instead on integrating the characteristics of these approaches to form a multi-stage pathway.

It should be emphasized that traditional villages and their architectural heritage are numerous, meaning that RIPC approaches must be cost-effective under limited resources [8], [30]. AHTV also faces issues such as material decay, structural deterioration, and natural disasters. Many of these risks require refined techniques for reliable diagnosis [68]. The present study proposes a conceptual framework of RIPC (Fig. 4), comprising two stages of initial risk screening and in-depth diagnosis, based on the above findings. VDAA is a cost-effective risk identification approach that quickly identifies risk types and locations during the initial risk screening phase. Significantly, its high efficiency and accuracy (1309 times more efficient than manual inspection, mAcc=90.23%) have been validated in previous studies [84], [85]. Collecting visual data with devices such as smartphones enables non-specialists to participate, lowering costs and easing the shortage of specialists. Although applying deep learning-based VDAA is complex, this primarily reflects the model establishment process. During the risk extraction phase, its automation and batch processing capabilities alleviate the need for specialists, meeting the demands for lower costs and higher efficiency.

For in-depth diagnosis, we suggest on-site observations, which adapt well to different risks and complex environments. These capabilities are difficult to achieve through monitoring or PCDAA [43], [77]. The results of on-site observations can inform decisions about whether more precise techniques are necessary. For instance, monitoring is appropriate for tracking dynamic changes in real time, while PCDAA is helpful for capturing surface textures and subtle structural details. However, these methods are often costly and technically demanding, so their use should be critically evaluated to avoid wasting resources. If on-site observations already provide sufficient information, there is no need to use additional tools. Meanwhile, secondary data can also be incorporated into the risk extraction process, helping to identify changes in traditional villages and their surrounding environments through comparison and analysis with current information.

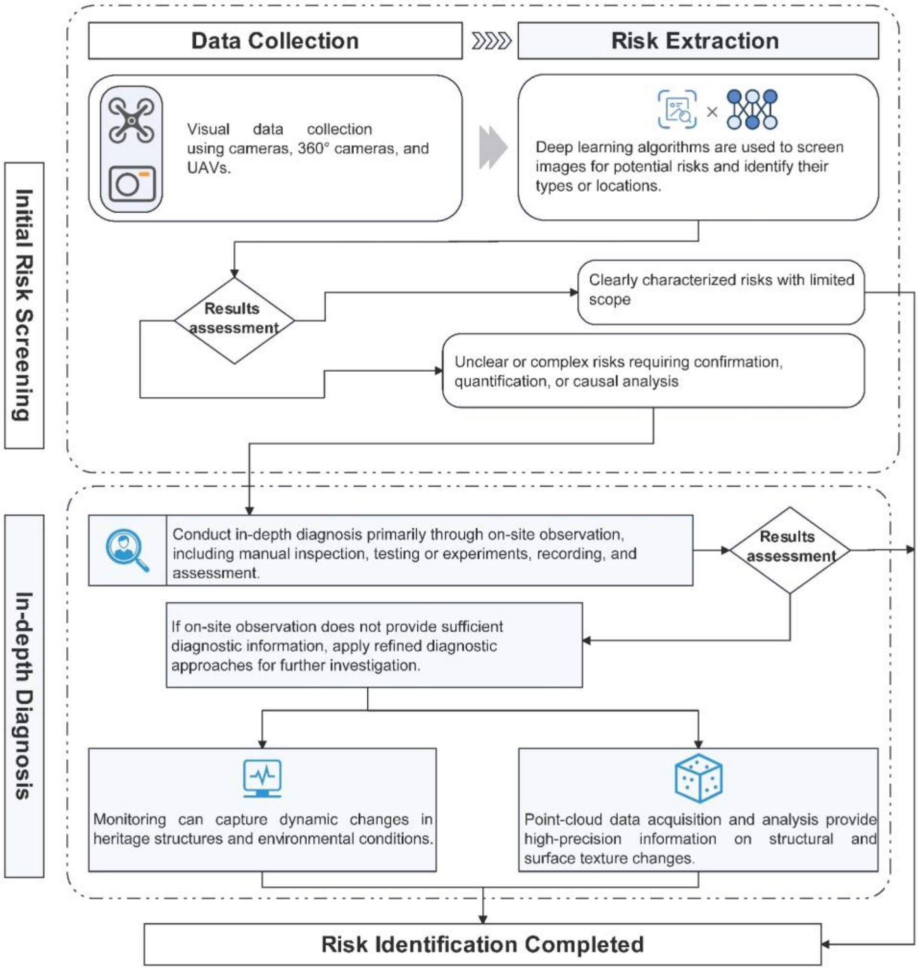


Fig. 4. Conceptual framework of risk identification in preventive conservation for AHTV

Notably, not all identified risks require entering the subsequent phase for in-depth diagnosis. Studies indicate that when risk types are clearly characterized and limited in scope, such as missing roof tiles or weathered or peeling wall surfaces, RIPC can be completed through image analysis alone [50], [86]. Conversely, in cases involving subtle surface features, complex conditions, or the need for additional quantification of damage and its causes, an in-depth diagnostic stage becomes necessary.

This study systematically synthesizes the RIPC practices in architectural heritage and proposes an integrated RIPC conceptual framework for AHTV. Unlike many previous studies, this paper emphasizes the applicability of the approaches under practical constraints such as multiple coexisting risks, limited financial and conservation resources, and complex spatial environments. In addition, many historic rural areas worldwide face similar challenges, and the framework proposed in this study can also provide a reference for RIPC practices in these regions. It is important to acknowledge that these analyses and descriptions are summarized from various empirical studies in this review. They primarily represent qualitative judgments based on literature rather than testing under standardized conditions. Furthermore, the study did not further compare the differences among tools in each pathway. For instance, deep-learning algorithms may differ in the risk types they identify, as well as in cost, accuracy, and efficiency. Future research should use case studies to validate the effectiveness of the framework. Subsequent work should also focus on developing dedicated datasets for traditional villages to improve the accuracy of deep learning models.

Conclusions

This review assessed the applicability of existing RIPC approaches to AHTV under settlement-scale, multi-risk, and resource-constrained conditions. Although digital and high-precision methods are increasingly prominent, no single approach meets all applicability requirements. The complementary capabilities of the reviewed approaches therefore provide the basis for a two-stage framework combining broad initial risk screening with targeted in-depth diagnosis. Initial screening is intended to identify potential risks efficiently across large numbers of heritage assets, whereas in-depth diagnosis is reserved for cases requiring more detailed investigation. During initial risk screening, deep learning-based VDAA offers cost-effective and high-efficiency batch processing. Importantly, the operational simplicity of VDAA during the data collection stage allows the involvement of non-professional groups, helping to broaden data sources and enhance the applicability of the RIPC framework. During the in-depth diagnostic phase, on-site observations can identify and document multiple risk types under complex spatial conditions. Refined diagnostic approaches, such as PCDAA and monitoring, provide additional dynamic, high-precision information. This division of roles helps allocate limited conservation resources more effectively by reserving more intensive resources for in-depth diagnosis rather than initial risk screening.

The contribution of this study is to propose an integrated RIPC pathway that links technological capabilities with the practical constraints of AHTV. It also supports a shift in traditional village conservation from post-damage repair toward cyclical and proactive risk identification, thereby strengthening the role of preventive conservation. More broadly, the proposed pathway may provide a reference for other rural heritage properties facing similar conservation challenges and limited financial resources.

Abbreviations

ICOM-CC	International Council of Museums-Committee for Conservation
SfM-MVS	Structure from Motion- Multi-View Stereo
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
UAVs	Unmanned Aerial Vehicles
ATR-FTIR	Attenuated Total Reflectance-Fourier Transform Infrared spectroscopy
SHM	Structural Health Monitoring

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