


Review

Research on the Acoustic Environment of Heritage Buildings: A Systematic Review

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Abstract: As a significant part of heritage building protection, an increasing number of researchers pay attention to the study of the acoustic environment. The purpose of this study was to provide a clear understanding of the status quo of acoustic environment research on heritage buildings and discuss future development directions through a systematic literature review. The PRISMA protocol was used to conduct a systematic evaluation based on 42 studies on the acoustic environment of heritage buildings retrieved from databases such as the Web of Science. Research on the acoustic environment of heritage buildings mainly focused on the following four aspects: the acoustic environment with different functions, the influence of building materials on the acoustic environment, the digitization of acoustic heritage, soundscape measurement, and perception of the historical area. Second, this study discusses the development trend of acoustic environment research of heritage buildings and the shortcomings of current research. Finally, this study provides a comprehensive overview of the acoustic environment research of heritage buildings and offers suggestions for future research.

Keywords: architectural acoustics; heritage buildings; acoustic environment; architectural soundscape; acoustical heritage



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1. Introduction

Heritage buildings, also known as historical buildings, are legacy buildings for human civilization and an important carrier of cultural heritage, including those buildings, structures, cultural relics, and areas with historical, aesthetic, and architectural significance [1]; any related buildings with cultural significance can be considered as heritage buildings. Based on the basic meaning of culture, heritage buildings range from historic buildings, structures, ancient sites, traditional towns and homes, and gardens. A city, site, church, old manual mill, disused wharf, and old fire station can all be deemed heritage buildings. Factories, furnaces, and old shipyards left over from the Industrial Revolution can also be considered heritage properties [2]. Additional interest has been paid to tangible external structures to protect heritage buildings. The intangible sound environment inside and outside of the building also plays an important role in heritage building protection [3]. “Sound environment” refers to the environmental sound condition perceived by the human ear; all sounds that can be heard by the human ear belong to the sound environment. The factors influencing subjective and objective evaluations of the acoustic environment include social background, psychological state, sound preference, and noise acceptability [4–6]. The branch of architectural acoustics mainly studies the differences in the sound effects of different architectural designs and their influence on human perception from the perspectives of sound, sound field, and human cognition. As heritage buildings such as churches, temples, and museums are rich in religious significance and have high aesthetic value, the study of their acoustic environment has always been of importance to researchers.

1.1. Building Environment and Noise

There are two types of sounds in the urban public environment. One is what people want to appreciate, accept, and listen to, including language communication, music, and art enjoyment, and the natural soundscape, such as birds singing and insects, springs, and waterfalls. The other is noise, which interferes with sleep, thinking, and work efficiency [7]. The mixed use of land caused by rapid urbanization makes the built environment more complex, and various noises have brought a huge threat to people living in the city [8], increasing attention to the building acoustic environment. As an integral part of sound, noise is included within the scope of soundscape research [9]. Architecture belongs to the science of human settlement. An urban environment requires a good acoustic environment; urban public spaces and residential areas must be well designed for environmental acoustics [10,11]. Not only does the acoustic environment of urban public spaces need to be reasonably designed, but the acoustic environment of the building interior must also be considered. Different types of building noise are required to meet the corresponding design standards, and building noise beyond international standards affects human health [12]. Low-frequency noise (not perceived by individuals) also has various effects on human health, such as causing sleep disorders and hearing loss, and increasing the likelihood of cardiovascular diseases [13].

The building acoustic environment mainly includes two aspects: the building noise environment and the indoor sound quality environment. Among these, building noise environments are mainly divided into interior noise environments and exterior noise environments [7]. The interior noise environment refers to the indoor noise requirements that the rooms or functional spaces inside the building must meet. External noise refers to the daily activities in the building, the mechanical and electrical equipment, and the roof radiating noise outside of the building, such as railway stations, airports, and other buildings that are prone to traffic noise. To obtain a good noise environment inside the building, it is necessary to have an effective sound insulation design of the building maintenance structure and the noise and vibration control design of the electromechanical equipment. Moreover, to avoid noise interference outside of the building, it is necessary to have a successful sound insulation design of the building maintenance structure and the noise reduction design of the building external equipment [14,15]. Building materials play an important role in reducing noise and improving comfort in the built environment. For sustainable development, the thermal properties of natural materials have been studied to improve building energy performance. For example, gypsum with recycled materials, natural fiber plasters, and building insulation materials made of natural fibers can not only improve the energy performance of new and existing buildings but also improve environmental comfort [16]. The indoor sound quality environment primarily focuses on the indoor listening effect. Professional acoustic spaces, such as concert halls and theaters, require professional acoustic designs to achieve good listening effects. There are many indoor sound quality indicators, of which reverberation time (RT) is recognized as the most significant. Other sound quality indicators include the clarity index (D50), clarity index (C80), speech transmission index (STI), and sound field unevenness [17]. These sound quality parameters represent a certain subjective listening experience, and the sound quality parameters have different preference ranges in various functional spaces. To obtain an effectual indoor sound quality environment, it is necessary to have a successful body design, sound absorption treatment, and diffusion treatment.

1.2. The Importance of Research on the Acoustic Environment of Heritage Buildings

Heritage buildings, also called historical buildings, are built with historical materials and a carrier of human historical and cultural information; therefore, the preservation of heritage buildings is extremely important. The three main factors determining whether a property should be classified as a heritage building are its historical significance, integrity, and environment [18]. As a significant environmental variable, sound has accompanied human civilization from the beginning, helping to understand the world and shape cul-

ture [19]. Therefore, the preservation of heritage buildings not only protects architectural forms but also interior and exterior acoustic building environments.

Recently, the soundscape has also been applied to the protection and restoration of cultural heritage [20]. By restoring ancient sound scenes through modern technology, tourists can more fully experience the historical atmosphere of the site, thus enhancing civilization recognition and awareness of heritage building protection. Furthermore, “sound of the past” is also considered as intangible cultural heritage [21,22]. It is not only the soul of churches, temples, museums, and other ancient buildings, but also the landscape resources of historical and cultural blocks, hence the term “acoustic heritage”. VR technology is used to reproduce past sounds, what it means to use it, and how to let modern individuals experience and understand sounds from the past [23,24]. Heritage buildings exist in many forms as carriers of civilization inheritance, and heritage buildings with different functions and forms have different requirements for the acoustic environment [9]. For example, religious buildings such as churches and temples focus on the integration of sound and spirituality. Venues such as theaters and concert halls target indoor acoustics, while heritage buildings used for modern purposes such as classrooms and auditoriums concentrate on sound insulation and the speech transmission index (STI). Sound is an external stimulus for individuals; owing to differences in personal life experiences and cultural backgrounds, the same sound may have different psychological feelings of like or dislike [25]. The soundscape of historical blocks in many heritage buildings also has a significant impact on visitors’ experiences. Therefore, research on the acoustic environment of heritage buildings covers a wide area and is of great significance to the protection and preservation of heritage buildings.

Regarding the need for heritage building acoustic environment protection and rapid development of architectural acoustics technology, it is necessary to conduct a systematic literature review to summarize and update the latest research results on heritage building acoustic environments. This study summarizes, classifies, and demonstrates the research emphasis and development trends in the acoustic environment of heritage buildings. This study attempted to address the following questions: (1) What functions does the research on the acoustic environment of heritage buildings focus on and what aspects does it mainly study? (2) What are the effects of different building material types on the acoustic environment of heritage buildings? (3) What is the significance of the soundscape in historic areas for the conservation of heritage buildings? (4) How is the digitalization of sound heritage achieved?

2. Materials and Methods

This study adopted the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) method as the main research method. Based on the latest guidelines [26], PRISMA should include the following steps: identifying sources of information, developing eligibility criteria, defining search strategies, determining data screening methods, running data collection processes, and result analysis and discussion.

A PRISMA flowchart of the selection process is presented in Figure 1. After three select phases, identification, and two screening stages, 42 studies met the established selection criteria. The literature used in this study includes peer-reviewed articles searchable through common databases, such as Web of Science, Scopus, Science Direct, and Web of Knowledge, and edited in English. The following keywords were used as initial search criteria: “heritage buildings”; “acoustic environment”; “soundscape”; “architectural acoustics”, and “acoustic heritage”. These keywords were used to search for terms in the titles, abstracts, and keywords. The final selection criteria were as follows: (1) published in English; (2) research that evaluated the acoustic environment of heritage buildings; (3) studies that evaluated the heritage building soundscape; and (4) not limited by date.

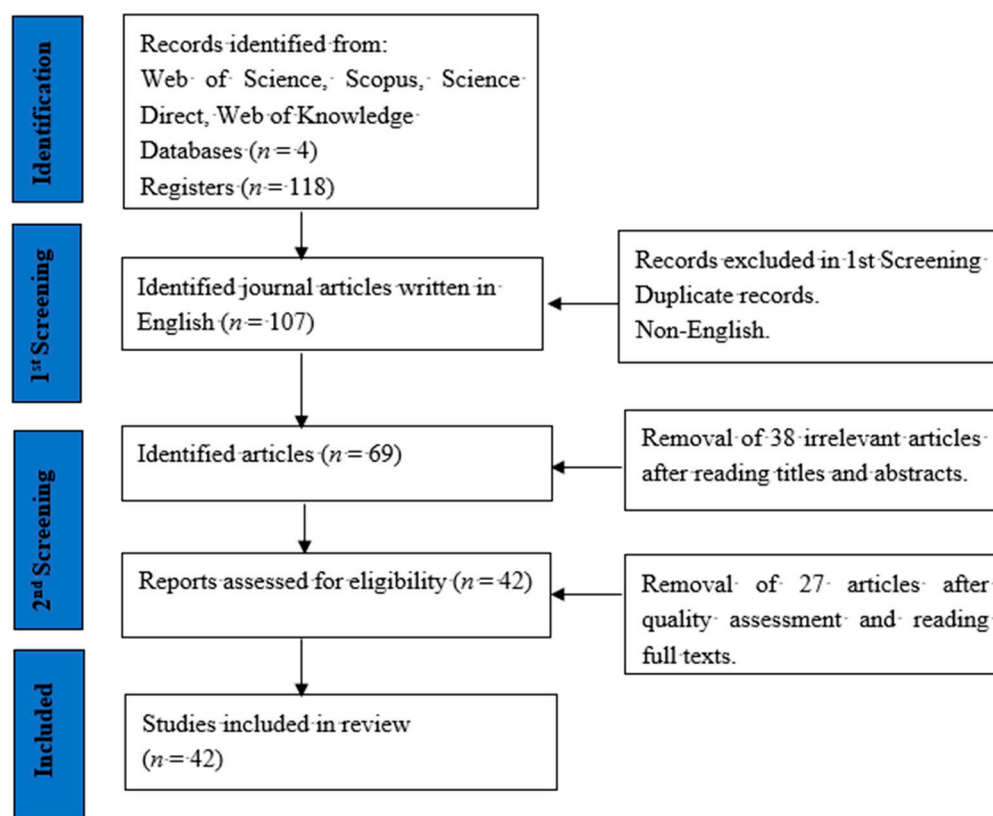


Figure 1. Flowchart of articles screened in this study.

These studies were read in their entirety to determine the research methods, priorities, and conclusions that were used. Subsequently, we found that each relevant study on the acoustic environment of heritage buildings has significant differences in specific research objectives and contents. According to the literature, meta-analyses are not recommended when studies are highly heterogeneous [27]; only systematic reviews of the main relevant research areas on the acoustic environment of heritage buildings were performed.

3. Results

3.1. Descriptive Analysis

In this section, the yearly distribution of the included studies was analyzed. As shown in Figure 2, the earliest article researching the acoustic environment of heritage buildings was published in 2005, but related research began to increase after 2015. The highest number of studies were published in 2019 and 2020. Research on the acoustic environment of heritage buildings has been increasing in recent years.

The included studies were classified according to the country of the first author. The results are shown in Figure 3; most of the studies consistent with the research scope were from Spain (12), Turkey (4), and Italy (3). Authors from China, Indonesia, Japan, Greece, and France were also interested in this field.

3.2. Results Analysis

Through the systematic review process, acoustic environment research of heritage buildings can cover the following four main aspects: the acoustic environment measurement of heritage buildings, the application of virtual reality technology in the reconstruction of heritage architecture soundscapes, the perception of cultural heritage and historical sites, and the acoustic reconstruction and design of heritage buildings.

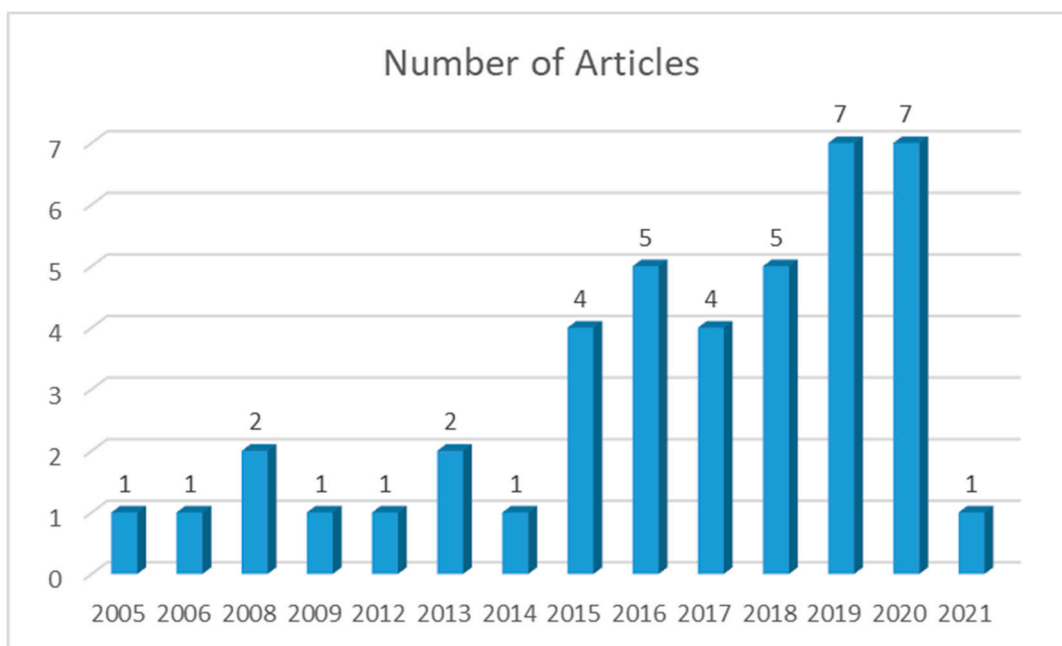


Figure 2. Number of articles published per year.

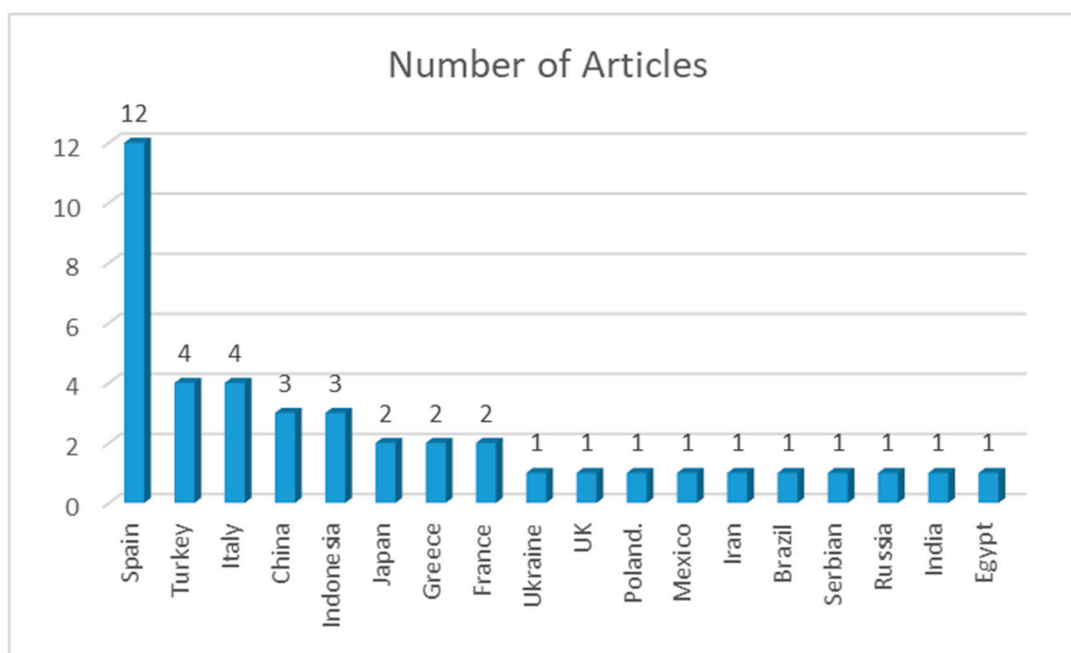


Figure 3. Number of publications per country (the country of first author).

3.2.1. The Acoustic Environment of Heritage Buildings with Different Functions

The measurement objects of the acoustic environment of cultural relic buildings mainly focus on religious buildings such as churches and temples, public space buildings such as theaters and museums, and some buildings with teaching spaces. The main research methods used were acoustic field measurements and acoustic simulations. The building type, geographical location, research methods, research focus, and conclusions of the selected studies are listed in Table 1.

Table 1. Summary of selected research assessing the acoustic environment of heritage buildings.

No.	Building Function	Author, Year, and Reference	Building Types	Case Building and Location	Methodology	Research Focus	Research Conclusion
1	Religious buildings	Álvarez-Morales et al. (2016) [28]	Church	Andalusia Cathedral; Spain	Measurements	Acoustic characteristics and influencing factors of different areas inside the cathedral.	The acoustic properties of early reflected energy and speech sound, such as reverberation, spaciousness, strength, and clarity, are significantly dependent on the location of the sound source and its areas of influence.
2	Religious buildings	Álvarez-Morales et al. (2019) [29]	Church	Bristol Cathedral; UK	Measurement and simulation	Acoustic characteristics	The sound experience is different in various spaces inside the cathedral.
3	Religious buildings	Álvarez-Morales et al. (2014) [30]	Church	Malaga Cathedral; Spain	Measurement and simulation	Acoustic characteristics	The interdependence between sound source position and listener position in different areas of the cathedral is analyzed.
4	Religious buildings	Suárez et al. (2016) [31]	Church	Maior Ecclesia of Cluny; France	Simulation and measurement	Virtual reconstruction of acoustic heritage	The long reverberation time brought about by the spatial structure of the church enhances the divinity.
5	Religious buildings	Berardi et al. (2015) [32]	Church	The Palatine Chapel of the Royal Palace in Caserta; Italy	Measurements and simulation	Acoustic interventions that churches need to cater to modern uses.	Without compromising the aesthetic value of the building, heavy curtains and transparent vibrating panels along the side walls effectively reduce reverberation time to meet the needs of modern use.
6	Religious buildings	Elicio and Martellotta (2015) [33]	Church	Orthodox church of San Nicola; Russia	Measurement and documentation analysis	Acoustic characteristics	The acoustic characteristics of churches are related to their architecture. Acoustics is a cultural heritage that is strictly related to architecture itself.
7	Religious buildings	Pedrero et al. (2015) [34]	Church	Toledo Cathedral; Spain	Measurement	Acoustic characteristics	Different spaces in cathedrals have various acoustic characteristics.
8	Religious buildings	Dorđević et al. (2019) [35]	Church	Lazarica Church; Serbian	Measurement and simulation	The relationship between the acoustic characteristics of the church and its architecture.	Closing the dome with a flat ceiling did not show any significant impact on T30, but it lowered speech intelligibility. The height of iconostasis showed no significant influence on the acoustics of Lazarica church.
9	Religious buildings	Oldham et al. (2008) [36]	Mosque	Four historic mosques in Cairo; Egypt	Measurement and simulation	Acoustic characteristics	The architectural model of a mosque has a greater impact on its acoustic characteristics.
10	Religious buildings	Syamsiyah et al. (2016) [37]	Mosque	The Grand Mosque of Yogyakarta; Indonesia	Measurements and questionnaire	Evaluate the soundscape of the mosque.	Acoustic heritage is an intangible culture and should be studied using a combination of quantitative and qualitative methods.
11	Religious buildings	Zhang et al. (2016) [38]	Buddhist Temple	Four typical Han-Chinese Buddhist Temples; China	Measurements and questionnaire	Soundscape features of Chinese Buddhist temples and perceptions of visitors and influencing factors	Relevant religious factors such as religious belief of respondents and frequency and purpose of visiting the temples play a significant role in soundscape evaluation of Chinese Buddhist temples.
12	Religious buildings	Soeta et al. (2013) [39]	Buddhist Temple	Japanese Buddhist temples; Japanese	Measurement and simulation	Acoustic changes produced by Buddhist ritual changes in Japanese temples and their influencing factors.	The change in direction improves speech intelligibility, and the asymmetric property of direct sound and complex reflections from the altar and side wall increases the apparent source width.
13	Religious buildings	Soeta et al. (2012) [40]	Church	Four churches in Nagasaki; Japanese	Measurement	Acoustic changes and influencing factors of the change of old and new Catholic liturgy in Japanese churches	The change in liturgy has improved speech intelligibility and made the apparent source width smaller.
14	Religious buildings	Manohare et al. (2017) [41]	Buddhist Temple (Stupa)	Deekshabhoomi Buddhist monument; India	Measurements and simulation	Evaluating the acoustical condition in the monument and its impact on Buddhist chanting and other religious activities.	The structure is deemed appropriate for hosting Buddhist chanting and meditation but not appropriate for speech-related activities.

Table 1. Cont.

No.	Building Function	Author, Year, and Reference	Building Types	Case Building and Location	Methodology	Research Focus	Research Conclusion
15	Religious buildings	Galindo et al. (2009) [42]	Church	Mudejar Gothic cathedral; Spain	Measurements and stimulation	To explore the application scenarios of new building materials in the reconstruction of the ancient acoustic environment.	Acoustic simulation procedures using iterative processes are suitable for the reconstruction of ancient acoustic environments of buildings with rich heritage and enable reliable assessment of maintenance, restoration, and conditioning effects for new uses.
16	Cultural buildings	Aknesil et al. (2005) [43]	Theater	Yıldız Palace Theater; Turkey	Measurements and Literature research	Evaluate the acoustics of the historic theater and compares to the documentation.	The theater is suitable with respect to its present functions of speech and chamber music, as it was in the past.
17	Cultural buildings	Stumpf Gonzalez et al. (2018) [44]	Auditorium	Padre Werner Unisinos auditorium; Brazil	Measurement and simulation	Evaluate the acoustic quality of the auditorium and explore the influencing factors.	The acoustic quality of the auditorium is more suitable for speaking events than for musical performances.
18	Cultural buildings	D'Orazio (2020) [45]	Museum	The National Archaeological Museum of Florence; France	Measurements and model validation	Model and method for improving acoustic comfort of museums by controlling human noise	A maximum number of visitors and visit time should be established to keep proper acoustic comfort.
19	Cultural buildings	Rubacha et al. (2019) [20]	Theater	Maria Zankovetska Theater; Ukraine	Measurements	Analyze the acoustic parameters inside the theater before and after changing the armchairs.	The most important impact on the acoustic parameters of the theater is provided by upholstered armchairs with high sound absorption, which is related to their construction, upholstery thickness, quantity, and arrangement in the room.
20	Cultural buildings	Ciaburro et al. (2020) [46]	Theater	Odeia of Pompeii and Posillipo; Greece	Simulation	Assess the architectonic and acoustics	Roofed buildings such as the Odeon are perfect for music, song, and speeches.
21	School architecture	Maffei et al. (2008) [47]	Classroom	Different classrooms in an historical Monastery Architecture of the Second University of Naples; Italy	Measurements and experimental methods	Acoustic correction for reverberation and speech intelligibility in historic building classrooms using novel materials	Simple boards built with sustainable materials can improve the reverberation and speech intelligibility of university classrooms inside historical buildings
22	School architecture	Iannace et al. (2013) [48]	Classroom	Classrooms of the Faculty of Architecture of the Second University of Naples (SUN); Italy	Measurements and simulation	The acoustic correction effect of green material acoustic absorbing board with aesthetic effect was tested.	Using green material panels made from giant reeds allows for good acoustic correction of historic building classrooms.
23	School architecture	Bautista Kuri et al. (2019) [49]	Classroom	Postgraduate Classroom of the National Autonomous University of Mexico; Mexico	Measurement and simulation	Find a suitable solution to reduce classroom noise.	The double skin façade (DSF) proposal can reduce external noise in the classroom and improves acoustic comfort.

Religious buildings, namely churches and temples, are the main research subjects in the acoustic environment of heritage buildings. Acoustic research on churches has mainly focused on the internal sound field of their monomers, and they have developed specialized church acoustics and accumulated numerous achievements [50]. The impulse response method is commonly used to evaluate church acoustics, and the common parameters include RT, EDT, STI, and D50. Álvarez-M Alvarez-morales et al. [28] conducted a study on the Andalusia Church's acoustic environment. To realize the church's multipurpose functions, such as worship, concert, and singing, six test points were selected and five sound sources were placed to test T30 performance at different frequencies in different areas. Simultaneously, the suitability of the language sounds in different areas of the church was tested and determined. The quality of the music from the altar or choir was poor, and the use of the pulpit slightly improved the STI (singing received by the audience during

assembly). The early reflected sound energy was not only affected by the layout of the church but also showed better geometric and acoustic properties when the source was in the rear position than in the choir position [29]. Moreover, Álvarez-Morales et al. [30] studied the methodological theory of the gothic church environment and its application in Malaga Cathedral, mainly by determining monophonic and dual-channel impulse responses at different receiving points for different sound source locations. Suarez et al. [31] established a model to simulate the sound of Maior Ecclesia of Cluny in France and discussed the relationship between the spatial components of the church and how the elements form music by placing two sound sources in this location. The STI of empty and full seats in the six church positions were then measured, and the biased evaluation partition corresponded. A long reverberation time resulted in the grand auditory experience of Gregorian singing and improved spirituality. Berardi et al. [32] studied sound interference in the lectern of Caserta Palace in Italy and also studied C80, EDT, T30, and D50 on various octave frequencies through field testing and model simulation comparisons. The soundness of each method at 250 and 1 kHz frequencies was measured. Elicio et al. [33] studied the sound of the Russian Orthodox Church, used a new microphone array measuring tool, and identified the arrival direction of the reflected sound. Architectural factors played a significant role in acoustic performance and verified the hypothesis that acoustics are as important as church architecture for cultural heritage. Pedrero et al. [34] conducted an extensive acoustic measurement study based on the relationship between architectural space and the liturgical function of Toledo Cathedral in Spain and concluded that acoustic space is particularly suitable for the respective liturgical function. Đorđević et al. [35] used the multidisciplinary method of acoustic archaeology to test the acoustic parameters selected in the medieval Orthodox Lazarica church in eastern Europe and simulated the sound field. Parameters such as T30, EDT, and the STI detected different space occupations inside the church under the acoustic effects.

In addition to churches, the acoustic environment of other religious buildings has mainly been measured in mosques and Buddhist temples. During the acoustic environment study of mosques and Buddhist temples, multiple buildings of the same type were typically included to measure the acoustic environment and summarize the acoustic characteristics. Oldham et al. [36] conducted detailed architectural and acoustic analyses of collected samples through a comprehensive historical survey of mosques built from the 9th to 18th centuries and studied the acoustic characteristics of four modes representing the architectural development of historic mosques in Cairo built during this time. Shamiyah et al. [37] investigated the soundscape of the Grand Mosque in Yogyakarta, using a combination of quantitative and qualitative methods. Quantitative methods included measuring impulse responses, background noise, and soundscape spaces inside and outside the mosque. Qualitative methods refer to descriptions of objects and participants in religious and cultural activities. Qualitative data can explain the acoustic phenomena that occur. Zhang et al. [38] selected four typical Chinese Buddhist temples for investigation, carried out field measurements of the sound levels in the four temples, and conducted a questionnaire survey on the subjective evaluation of visitors' sound. The results show that there was a significant correlation between the temple's sound preference and the articulation value of the sound in psychoacoustic parameters. For objective factors, there was a significant correlation between the measured sound level and soundscape evaluation. For subjective factors, age, occupation, religious beliefs, purpose, temple visit frequency, and education level were significantly correlated with soundscape evaluation. Buddhism has a wide and far-reaching influence in Asia, and Buddhist architectural heritage is also widely distributed. Thus, there have been many achievements while studying the acoustic environment of Buddhist architectural heritage [39]. By measuring acoustic parameters such as reverberation time and early decay time, Soeta et al. [40] studied the influence of changes in sound and direction during liturgy on the acoustic environment of four Catholic churches in Japan and found that new Catholic liturgy improved articulation and reduced the apparent source width. Manohare et al. [41] evaluated the acoustic characteristics of Deekshabhoomi (a hollow

Buddhist memorial tower building in India) under occupied and unoccupied conditions, established a virtual simulation model to verify the field measurement data, evaluated the acoustic behavior of the worship space, and compared it to other research. The pagoda has a large reverberation time and the same structure as other worship spaces. The building is considered suitable for Buddhist chanting and meditation, but not for activities related to speech.

Theaters, auditoriums, museums, and other cultural buildings are also important research subjects for the acoustic environments of heritage buildings. As a professional acoustic space, research on the acoustic environment of theaters focuses on the sound effect inside the building; therefore, the research method is mainly field measurement. Ciaburro et al. [20] evaluated the acoustic characteristics of Odea and Posillipo in Pompeii in the presence of the original roof system using commercial software (Odeon, Room acoustic software, Lyngby, Denmark), indicating that these buildings are suitable for music, songs, and speeches. Aknesil et al. [43] evaluated the acoustic properties of the Ottoman classical theater Yiliz Palace and compared them to the literature, concluding that the acoustic effects of the theater are the same as in the past, and that the speech and chamber music functions are appropriate. Research on the acoustic environment of museums, auditoriums, and other non-acoustic spaces focuses more on the evaluation of indoor acoustic effects corresponding to the types of acoustic activities, and the research method is a combination of field measurements and model simulations. Stumpf-Gonzalez et al. [44] evaluated the acoustic quality of a multipurpose auditorium at the Unisinos campus in Sao Leopoldo, Brazil, and modelled the auditorium using the acoustic simulation software Cat-Acoustics. However, it is not suitable for music presentations. Simultaneously, a constructive scheme to improve the acoustic quality of an auditorium was discussed. D’Orazio et al. [45] believe that the acoustic comfort level of museums with a large number of visitors is mainly affected by human noise, and most museums are heritage buildings that cannot be acoustically modified. Therefore, a dynamic model to control the number of visitors and visiting time is proposed to improve the acoustic comfort level of museums. Berardi et al. [33] and Rubacha et al. [46] investigated the use of new materials and finishes to improve the acoustics of heritage buildings for contemporary use.

The use of heritage buildings as classrooms is another practice that still exists today. However, most of the sound environments of heritage buildings cannot meet the requirements of modern teaching owing to their age. For example, building restrictions are often imposed to preserve historical heritage, and acoustic measurements in classrooms show high reverberation time values, which indicates an unfavorable environment for speech reception. Some historic buildings were also acoustically unsuitable for teaching when they were repurposed for use as school grounds [51]. Therefore, it is necessary to achieve acoustic correction by transforming building materials under the premise of heritage building protection. Three articles examined the relationship between the acoustic environment and materials of heritage buildings, aiming to solve the noise problem or improve the acoustic comfort of heritage buildings such as historic classrooms and auditoriums that are still in use.

The measurement objects of the acoustic environment of heritage buildings with different functions mainly focus on religious buildings such as churches and temples, public buildings such as theaters, museums, and auditoriums, and classrooms converted from historical buildings to modern uses. The relevant research mainly obtains the acoustic characteristics of buildings by means of sound field measurement and acoustic simulation, and seeks to improve acoustic conditions. This research has made a useful attempt in the protection and modern application of the acoustic environment of heritage buildings.

3.2.2. Influence of Building Materials on Acoustic Environment of Heritage Buildings

A close relationship exists between the acoustic performance of a building and the building materials. Since most of the heritage buildings that remain today have undergone many transformations and renovations or have changed their original uses, alterations in

architectural features such as building materials have also affected the sound environment of buildings [52]. Researchers have studied the influence of various building materials on the acoustic environments of heritage buildings. In recent years, with the in-depth research on sustainable acoustic materials [53], sustainable materials have been gradually applied to the acoustic transformation of heritage buildings. A summary of the acoustic environments of heritage buildings with different building materials is presented in Table 2. The building materials mentioned in the table refer to the materials related to the acoustic analysis in the relevant research and do not refer to the main building materials.

Table 2. Summary of the acoustic environments of heritage buildings with different building materials.

No.	Author, Year, and Reference	Building Materials	Building Types	Case Building and Location	Methodology	Material Position	Research Conclusion
1	Galindo et al. (2009) [42]	A variety of main materials	Church	Mudejar Gothic cathedral; Spain	Measurements and stimulation	Building main body	The iterative process undertaken and the estimation of the irregularities appear capable of adequately describing the acoustical characteristics of materials by means of their absorption and scattering coefficients.
2	Rubacha et al. (2019) [46]	Wood; fabric	Theater	Maria Zankovetska Theater; Ukraine	Measurements	The main space	Cushioned armchairs with high sound absorption have the greatest effect on theater acoustic parameters.
3	Maffei et al. (2008) [47]	Sustainable materials made from kenaf	Classroom	Different classrooms in the historical Monastery of the Second University of Naples; Italy	Measurements and experimental methods	The roof	Simple boards built with sustainable materials can improve the reverberation and speech intelligibility in university classrooms inside historical buildings.
4	Iannace et al. (2013) [48]	Green material panels made from giant reeds and kenaf	Classroom	Classrooms for Faculty of Architecture in the Second University of Naples (SUN); Italy	Measurements and simulation	The roof	Using green material panels made from giant reeds allows for good acoustic correction of historic building classrooms.
5	Bautista Kuri et al. (2019) [49]	A Double Skin Façade combining metal and photovoltaic glass	Classroom	Postgraduate Classroom in the National Autonomous University of Mexico; Mexico	Measurement and simulation	Noise barriers outside buildings	The double skin façade (DSF) proposal can reduce external noise in the classroom and improves acoustic comfort.
6	Macieira et al. (2020) [54]	Stretch membrane materials	Church	Carmo's church in Lisbon; Spain	Stimulation and measurements	The roof	Membrane materials have great potential to improve the acoustic properties of highly complex volumes.
7	Nowoświat et al. (2020) [55]	Spray-deposited insulating material	Church	A dome-shaped sacral room of the Pentecostal Congregation in Katowice in Silesia, Poland.	Measurements	The inside of the dome	Spraying insulation on the inside of the dome significantly improved the church's reverberation.
8	Sert, and Karaman (2021) [56]	Brick; wood	Masjid	Eight Masjids built on the Anatolian side; Turkey	Measurements and simulation	Building main body	During the renovation of the historic mosque, it is important to choose appropriate and sustainable materials according to the main building material to protect the original acoustic environment.

Maffei et al. [47] analyzed the acoustic performance of different classrooms in a historic monastery of the School of Architecture of the Second University of Naples and found that the acoustics were very poor in terms of reverberation and speech intelligibility, mainly due to the large volume and lack of absorbing materials, while the introduction of simple boards built with sustainable materials could achieve good results. Galindo et al. [53] estimated the

absorption coefficient of the new building material using an iterative process, conducted acoustic simulation in Mudejar Gothic cathedral, and compared it with the acoustic data measured in the field. The difference between the two parameters was discussed, and the application scenario of the new building material in the reconstruction of the ancient acoustic environment was constructed. Iannace et al. [48] used detachable sound-absorbing panels made of “green materials” such as reed and jute to acoustically modify a classroom in a historic building of the School of Architecture at the Second University of Naples. They measured reverberation time, speech clarity and other parameters under unoccupied conditions and compared the acoustic performance with the virtual model. It was verified that the acoustic correction effect of green material sound-absorbing board is good. Using the LimA Predictor program, Bautista Kuri et al. [49] tested two noise isolation schemes in a graduate classroom at the National Autonomous University of Mexico (UNAM) and demonstrated that a double skin façade combining metal and photovoltaic glass could bring classroom noise within standard acoustic comfort levels. Macieira et al. [54] take the museum transformed the heritage building Carmo Church, as an example, and investigated the effects of a stretch film roof combined with a retractable cross-vaulted ceiling on the acoustic characteristics of the building’s interior, confirming the potential of stretch film materials to improve highly complex volume acoustics. Nowoświat et al. [55] used acoustic measurements to evaluate the reverberation time of the domed sacrament chamber of the Pentecostal Church in Katowice, Silesia, Poland, and proposed a scheme of applying spray-on insulation to the inner surface of the dome for acoustic modification; this scheme effectively improves the reverberation conditions inside the church. Sert et al. [56] collected the acoustic data of eight Turkish Anatolia historical mosques by comparing the different materials and types of ceiling structures of the distribution of acoustic parameters and measured values of suitability, revealing the ceiling structure difference and material change to the same volume, which influenced the acoustic environment of the mosques. Rubacha et al. [46] studied the changes of acoustic parameters in the interior before and after changing armchairs of Maria Zankovitska, a theater in Lviv, after reconstruction, calibrated Hall’s numerical model with measured parameters, and calculated reverberation time T_{20} and the speech transmission index (STI) to evaluate the acoustics effect of the hall with an audience present. The results show that the influence of upholstered armchairs on the acoustic parameters of the theater is the greatest, which is related to the structure of upholstered armchairs, the thickness of upholstered armchairs, and the number and layout of upholstered armchairs in the room.

When heritage buildings are used for modern purposes, it is difficult for most of the acoustic effects to meet modern needs. Since the acoustic performance of buildings is closely related to the building materials used, the main body of heritage buildings cannot be substantially transformed for protection and aesthetic needs. Therefore, scholars have explored the use of detachable and transparent sustainable building materials or the establishment of composite sound insulation barriers on the outside of buildings to correct acoustic effects. The application and acoustic effect test of green sustainable building materials under the protection and aesthetic requirements of heritage buildings has made outstanding contributions to the modern application and protection of heritage buildings, as well as expanding the application field of sustainable building materials and acoustic materials.

3.2.3. Soundscape Measurement and Perception of Historical Areas

In addition to monomer buildings such as churches and temples, the soundscape of historical and cultural locations where heritage buildings are concentrated is also a key field of acoustic environment research. The acoustic environments of open-air theaters, places of worship, opera houses, and concert halls are an important part of architectural heritage [43]. The original acoustic environment of heritage architectural spaces is worth recording, protecting, and restoring, as they have played an important role in human history. Soundscapes, cultural heritage, and public spaces amplify each other in urban

life. The soundscape design of heritage building blocks can optimize urban historical and cultural spaces and improve the quality of urban life [57]. A summary of the research on soundscape measurement and perception of historical areas is shown in Table 3.

Table 3. Summary of research on soundscape measurement and perception of historical areas.

No.	Author, Year and Reference	Building Types	Case Building and Location	Methodologies	Research Focus	Research Conclusion
1	Brambilla et al. (2006) [58]	Urban historical Area	The old town of Naples; Italy	Soundwalk, interview, and measurements	Effects of traffic noise on soundscape perception and cultural identity.	The soundscape of Naples' old town is a strong indicator of cultural identity.
2	Kayma et al. (2016) [59]	Urban historical Area	An urban historic district of Ankara, Hamamönü; Turkey	Measurements, field surveys, and questionnaire surveys	Soundscape survey of historic urban areas.	The soundscape of the historical district plays an important role in maintaining the historical value of the urban environment.
3	Djimantoro et al. (2020) [60]	Urban Historical Area	Fathallah Square, Jakarta; Indonesia	Soundwalk, recalled in memory, and visual analysis	Soundscape survey of historic urban areas.	Sound source plays an important role in the study of soundscape, and good management of sound sources can create a sound environment to enhance regional historical value.
4	Tokgöz (2019) [61]	Industrial Heritage Area	Industrial Buildings in Eskisehir, Turkey	Literature research and interview method	Interview and reproduction of urban industrial heritage soundscape.	Past soundscape data contributed to gaining identity and perception of continuity by bridging the past to present and to the future.
5	Huang, and Kang (2015) [62]	Urban historical Area	Historic city center of Lassa, China	Measurements and soundwalk	Soundscape survey of historic urban areas.	Some sounds in traditional forms should be regarded as acoustic markers with "local characteristics" and must be preserved.
6	Torija, and Ruiz (2017) [63]	Monuments and historic sites	The Alhambra of Granada, Spain	Soundwalk and questionnaire surveys	Soundscape survey of historic urban areas.	The assessment and management of monuments and historic sites and the soundscape of related areas is an important measure to enhance the visitor experience.
7	Liu et al. (2019) [64]	A renovated historical block	The "Three Lanes and Seven Alleys" historical block in Fuzhou, China	Questionnaire survey and model analysis	Effects of soundscape perception on visitor experience in renovated historical blocks.	Different soundscape perception and visiting experience indicators are affected by various sound sources.
8	Montazerolhodjah et al. (2019) [65]	Historical urban open spaces	Two historic squares in city of Yazd, Iran	Questionnaire survey and related analysis method	Identifying and evaluating acoustic factors for acoustic comfort in urban historic spaces.	Motorcycle and car noise is the most important sound affecting acoustic comfort, while children's play, water, conversation, and business sounds are the most important factors affecting acoustic comfort in historic venues.

Using soundwalks, interviews, and laboratory listening tests, Brambilla et al. [58] investigated the impact of traffic noise on residents' perception of soundscapes and cultural identity. A soundscape that is more relevant to Naples' historical identity, the region's soundscape, is a strong symbol of Neapolitan cultural identity. Kayma et al. [59] investigated the integrity between the visual landscape and acoustic landscape features of Ankara's urban historical districts through questionnaire surveys, field observations, and sound level measurements. The findings show that the acoustic landscape plays an important role in maintaining historical value in the urban environment. Djimantoro et al. [60] studied the relationship between the sound source of Fatahira Square in Jakarta and the acoustic environment predicted in historical sites by combining sound walking and visual analysis. The results show that a comprehensive study of multi-sensory stimulation can increase the overall understanding of historical sites. Tokgoz et al. [61] defined the industrial heritage soundscape and summarized the past urban soundscape by interviewing residents and relevant research experts near industrial buildings in Eskishil, a city in central Anatolia, during the industrialization process during the Ottoman Empire, combined with retrospective recordings, videos, photos, and other materials. This revealed the acoustic

landscape of Lhasa’s historic urban area through other materials. It reveals the important role of industrial heritage in the urban soundscape. Huang et al. [62] analyzed the acoustic landscape of Lhasa’s historic urban area by means of field investigation and sound walking and found that the sound sources of the historic urban area can be divided into five types: environmental sounds, information sounds, religious sounds, natural sounds, and traffic noise. Some sounds that exist in their traditional forms should be regarded as acoustic markers with “local characteristics” for preservation. Torija et al. [63] conducted a field study of a historic monument site in Alhambra, Granada, Spain, using sound walks and questionnaires, and found that the perceived quality of the soundscape was primarily driven by the evaluation of the dominant sound. For a given location, the higher the proportion of visitors reporting a predominance of pleasant sounds, the better the reported soundscape quality and the overall impression. Based on a questionnaire survey and SEM structural equation model analysis of 298 tourists in the “Three Lanes and Seven Alleys” historical block in Fuzhou, China, Liu et al. [64] verified the impact of sound perception on the visiting experience of the historical block and found different soundscape perceptions and visiting experiences. The experience index is affected by some different sound sources, and the soundscape design during the renovation of the historic district should focus on the rational use of different sound sources. Based on a questionnaire survey of 632 foreign tourists and related analysis, Montazerolhodjah et al. [65] studied the soundscape and acoustic conditions affecting traditional and tourist field tourism in the historical context of the city of Yazd and found that motorbike and car noise was perceived as the most important sound affecting acoustic comfort, while children’s play, water, conversation, and business sounds were the most important factors affecting acoustic comfort in historic venues.

Related research on the soundscape of historical and cultural blocks with densely distributed heritage buildings emphasizes the subjective perception of people walking in urban public spaces. Therefore, qualitative and quantitative methods were combined in the research, such as soundwalks, questionnaires, experimental measurements, and a combination of interview methods. Considering our research, we summarized the subjective evaluation of various common sound sources in historical blocks and distinguished the positively and negatively perceived directional sound sources to explore the influence of different sound sources on the visiting experience, which is the sound source of historical blocks. Scene design provides a valuable reference.

3.2.4. The Digitization of Acoustic Heritage

As a consensus has been reached on acoustic heritage as being cultural [66], the digitalization of acoustic heritage has also become an important topic while studying the acoustic environment of heritage buildings. As the main material carrier of acoustic heritage, relying on virtual reality and other information and communication technologies, the digital reconstruction of past sounds in heritage buildings is the main technique to protect acoustic heritage [67]. Similar to the latest technology used in archaeological sites and the reconstruction of heritage sites, the main technologies used in the digitization of acoustic heritage are virtual reality and computer simulation [68]. During research on the restoration of the acoustic environment of heritage buildings using virtual reality technology, churches are still the main sites because of their heritage value, complexity, and versatility [69]. See Table 4 for a summary of the digitized acoustic heritage of heritage buildings.

Table 4. Summary of the digitization of acoustic heritage.

No.	Building Types	Author, Year, and Reference	Methodology	Application of Digital Technology
1	Theater, Church, and The Houses of Parliament	Katz et al. (2020) [67]	Literature research and simulation model development	Reconstruct the sound of history through acoustic simulations.
2	Church	Álvarez-Morales et al. (2017) [69]	Field measurement and simulation model development	Integrate visual and realistic sound clips

Table 4. Cont.

No.	Building Types	Author, Year, and Reference	Methodology	Application of Digital Technology
3	Church	Alonso et al. (2017) [70]	Field measurements and acoustic model comparison	Restore the sound fields of three historical choristers in their distribution configurations
4	Theater and Church	Đorđević et al. (2020) [23]	Case studies and 3D model simulation	Aural realization of sound heritage
5	Mosque	Suárez et al. (2018) [71]	Field measurements and simulation	Reconstruct the sound of history through acoustic simulations
6	Church	Sender et al. (2018) [72]	Literature research and simulation model development	Develop a geometrical model for acoustic simulation
7	Theater	Mirasol-Menacho et al. (2018) [73]	Integrated system development	Integrated graphics engine and acoustic system
8	Church	Álvarez-Morales et al. (2018) [74]	Experimental and simulation techniques	Use the software TUCT.V2 to obtain the acoustic parameters

Alonso et al. [70] used indoor acoustic simulation to reconstruct the sound field of three different choir configurations in Granada Cathedral, analyzed and compared the main acoustic parameters of each virtual reconstruction model, and then calibrated according to on-site measurement activities to systematically study the influence of indoor space conversion on the indoor acoustics of the cathedral. Đorđević et al. [23] showed the significance of virtual acoustic analysis for the reconstruction of theater architecture by referencing the research of the Roman theater in Crete, Greece. They described the archeological acoustic research of a medieval Serbian Orthodox temple to demonstrate the public desire for distant acoustic heritage. The author believes that the ability to digitize ancient sounds provides a valuable choice for us to experience historical and cultural heritage and maintains that the inclusion of sound heritage into the international heritage management framework is the prerequisite for its systematic digitalization. It is necessary to formulate guidelines for the digitalization of sound heritage and to present sound heritage through its audialization of sound heritage. In the field of archaeological acoustics, the historical sounds of heritage buildings are reconstructed using current simulation tools and virtual reality technology. Suárez et al. [71] reconstructed the original state of different spatial forms in the history of the mosque from the 8th to 10th centuries through field acoustic measurements of one of the representative Islamic temples in the West, the Akama Mosque in Cordoba, and through acoustic simulation of different models generated by these spatial forms. Archeoacoustics also focuses on the study of ancient environments used for performance using modern techniques. Sender et al. [72] developed a geometric model of acoustic simulation of Spain's al zillah, a 14th-century tower of Santa Maria Della Jose Jerome Abbey Church that has carried on virtual acoustics reconstruction, according to the building materials extracted from the historical documents and church acoustic research, different performances at different locations in the church, and listening to worship. Based on the integration of a graphics engine and acoustic system and the description of classical literature, Mirasol-Menacho et al. [73] studied an old theater in Valencia called "Oliveira Comedy" and showed the audibility technology of plays selected by different Spanish writers at that time. The virtual acoustic system based on Unity, FMOD, and Csound can provide a completely integrated and interactive realistic experience for users. Álvarez-Morales et al. [74] studied the acoustic properties of Murcia Cathedral in southeastern Spain through experiments and simulation techniques, measured the intelligibility and speech intelligibility values obtained in the audience area at the boundary required for good text/music communication, and proposed short-term intervention or acoustic support to create an audience in a specific situation to obtain a good auditory experience. As an effective tool in archaeological acoustics, virtual reality technology has been applied for the reconstruction of lost or destroyed heritage buildings. Similarly, virtual reality technology is also used as an efficient tool in archaeological acoustics to reconstruct the acoustic heritage of lost or damaged heritage buildings.

The protection of sound heritage in heritage buildings is as important as the preservation of the architectural form, and the reproduction of sound heritage is of great significance in promoting the protection of these buildings. Virtual reality technology is essential for

the reproduction of sound or acoustic heritage. While using virtual reality technology in the restoration of acoustic heritage, attempts have been made to integrate and combine acoustic simulation software such as TUCT.V2, the graphics engine, and the acoustic system, providing the visualization and auralization of heritage architectural acoustic heritage in the description of classical literature. It is convenient, enhances the visiting experience of heritage buildings, enhances the cultural identity of visitors, and has the potential to strengthen awareness of heritage building protection.

Furthermore, the digitalization of sound heritage involves updating sound source data acquisition methods. Sound sensing systems make mobile devices such as smartphones and tablets effective tools for low-cost data collection to monitor environmental noise [75]. Crowdsourced noise data using smart collections and mobile devices provide a universal monitoring of noise levels in cities and can be used to protect a place's acoustic heritage [76]. Currently, intelligent equipment to collect sound data is mainly used as an auxiliary tool to collect sound source data in the study of the sound environment of cultural heritage buildings. In the future, with the development of science and technology, this may become the main method of collecting sound data from heritage buildings.

4. Discussion

The acoustic environment is an important part of the physical environment of heritage buildings, while acoustic heritage is an important intangible cultural heritage. Combined with the actual needs of heritage building protection, the measurement and transformation of the acoustic environment of heritage buildings with various forms and functions should be accelerated. Simultaneously, the protection of the soundscape of the historical district is also of great significance in enhancing people's recognition of civilization and enhancing the awareness of heritage building protection, while restoring acoustic heritage and correcting the acoustic effects of heritage buildings, research, development, and testing of new sustainable materials are important. Acoustic simulation software and virtual reality (VR) technology are indispensable modern tools. There are several issues worthy of attention in the current status of research on the acoustic environment of heritage buildings.

4.1. Relationship between Acoustic Environment and Function of Heritage Buildings

The research emphasis on the acoustic environment of heritage buildings with different functions varies. Studies on the acoustic environment of religious buildings such as churches and temples, and cultural buildings such as theaters, have focused on the measurement of architectural acoustic characteristics, and the restoration and reproduction of acoustic heritage using digital technology. Research on the acoustic environment of heritage buildings, such as museums, classrooms, auditoriums, and other non-acoustic spaces, has concentrated on acoustic correction and noise control. Most studies on the acoustic environment of heritage buildings have focused on people with healthy hearing. The acoustic environment design of heritage buildings in public spaces, such as museums, should also consider the auditory feelings of different people to promote social equity. Based on this, Renel [77] portrayed the acoustic repulsion profile of museums and other heritage sites around the three central themes of sound accessibility and explored the key role of sound accessibility in enhancing the understanding of heritage architecture and promoting social equity. Different types of heritage buildings shoulder the function of public spaces, and the acoustic environment is an important part of the physical environment of public spaces. Therefore, research on the acoustic environment of various types of heritage buildings should be fully carried out, and more attention should be paid to them. Different types of heritage buildings function as public spaces, and the acoustic environment is an important part of the physical environment of these spaces. Therefore, research on the acoustic environment of various types of heritage buildings should be fully carried out.

4.2. Relationship between Acoustic Environment and Building Materials of Heritage Buildings

To protect historical and aesthetic value, most heritage buildings are not allowed to change their structure. Therefore, for heritage buildings used for modern purposes, acoustic correction using detachable materials and ornaments is a feasible approach. For acoustic correction of heritage building classrooms, the use of new and green materials on the roof of the detachable plate is a feasible approach [47,49]. In addition, methods to satisfy the acoustic transformation without damaging the appearance of heritage buildings are under constant study. Nowoświat et al. [55] evaluated the reverberation time of the dome-shaped sacral room of the Pentecostal Congregation in Katowice, Silesia, Poland, using acoustic measurements. A project of acoustic transformation with spray-on insulation applied to the inner surface of the dome was presented. This project effectively improved the reverberation conditions in the interior of the church. Berardi et al. [32] found a way to improve the acoustics of the Basilica Palatine to meet modern needs by using heavy curtains along the sidewalls and transparent vibrating panels to effectively reduce reverberation time, while respecting the aesthetic and historical value of the heritage building through field measurements and computer simulations. Fully developing the acoustic properties of new materials and sustainable materials for the acoustic correction of heritage buildings allows for heritage building protection. The modern use of heritage buildings also requires continuous acoustic renovation, especially for professional acoustic buildings such as theaters and concert halls. Combined with the needs of the modern uses of heritage buildings, the use of novel and sustainable materials for acoustic renovation has broad application prospects.

4.3. Preservation of Soundscapes in Historic Areas

The study of soundscapes in historic districts is of positive significance for the sound environment protection of heritage buildings. Compared to the sound environment, a soundscape is a more subjective concept [78]. Therefore, the soundscape research of historic districts not only includes sound source research in the overall environment of the district but also subjective visitor perception. Historic districts exist as urban public spaces, and heritage buildings are the main buildings in historic districts. The heritage building-centralized acoustic landscape of historic blocks is significant in increasing human understanding of history and experience, promoting awareness of the protection of heritage buildings and historical blocks. The measurement of acoustic landscapes of historic blocks and the investigation of subjective perceptions give full consideration to the role of acoustic heritage to promote cultural heritage, which should be a key focus in research on the sound environment of heritage buildings.

4.4. The Development Direction of Digitized Acoustic Heritage

Presently, the digitalization of acoustic heritage relies mainly on virtual reality technology and acoustic simulation programs, combined with literature descriptions, to achieve the reproduction of historical sounds in heritage buildings. The use of modern virtual reality and digital technology to reproduce ancient sounds recorded in the documents and books of heritage buildings not only enhances people's experience of ancient sounds and scenes but also has positive significance in improving people's historical and cultural identity of heritage buildings [79]. The research objects focused on churches, temples, theaters, and other types of heritage buildings that are less involved. Acoustic heritage relies on heritage buildings but should also be considered in the future development of the interior space of heritage buildings. Therefore, in terms of the digitalization of acoustic heritage, we can change the restoration of historical sounds to the perception of historical sounds and increase the exploration of the application scene of acoustic heritage.

5. Conclusions

A total of 42 studies were selected for systematic review and analysis. Through this process, the emphasis of current research on the acoustic environment of heritage

buildings is discussed, and possible future research directions are discussed. By analyzing the results, it was found that the acoustic environment research of heritage buildings can cover the following four main aspects: the acoustic environment of heritage buildings with different functions, the influence of building materials on the acoustic environment of heritage buildings, the soundscape measurement and perception of historical areas, and the digitization of acoustic heritage. The research objects focus on religious buildings, such as churches and temples, while there are few studies focusing on other building types.

The research subjects of the acoustic environment of heritage buildings with different functions mainly focused on religious buildings, such as churches and temples, as well as cultural buildings, such as theaters and museums. Currently, there are few studies on other types of buildings. In the future, it can be extended to compare heritage buildings of other functional types and to focus on the subjective feelings of different groups. As time progresses, some heritage buildings have been repurposed and their acoustic renovations and corrections need to be carried out without destroying the internal structure of the building. Therefore, the development of new materials, sustainable materials, and acoustic performance testing is necessary. Concurrently, the protection of the soundscape of historical areas is also of great significance in enhancing people's recognition of civilization and enhancing the awareness of heritage building protection. Therefore, in the future, the focus should be on the measurement and subjective perception of the soundscapes of historical blocks. Acoustic simulation software and virtual reality technology are indispensable tools for restoring and reproducing acoustic heritage. With the development of science and technology, the use of intelligent equipment may become the primary method to collect sound data from heritage buildings.

In general, this study conducted a comprehensive and systematic review and analysis of the acoustic environment research of cultural relics, clarifying the main research fields, applied research methods, and future development directions. The four aspects of acoustic environment research, including the population-oriented expansion of buildings with different functional heritage sites, the development and application of new and sustainable acoustic materials, the soundscape measurement and perception in historical areas, and the digitization of acoustic heritage, are valuable for continuing research. Therefore, researchers can fully understand the focus and development direction of acoustic environment research on cultural relics to promote the development of this research.

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