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Soundscape in religious historical buildings: a review

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Abstract

Over the past decade, a substantial body of research exploring soundscapes in religious historical buildings has emerged, yet a comprehensive summary of this work is lacking. This paper selects 74 typical studies of soundscapes in religious historical buildings published between 2011 and 2022 to conduct quantitative statistics and visualization analysis from a bibliometric perspective. The selected literature is categorized based on the type of religious building, Christian, Islamic, or Buddhist. The literature is further segmented according to the research subject, including sound field studies, sound analyses, and evaluations of the acoustic environment. The research methods employed are also differentiated and include sound field measurements, acoustic simulations, questionnaires and auralization procedures. The analysis reveals pronounced disparities in research foci depending on the type of religious historical building. For instance, studies on the soundscape in Christian churches tend to focus on objective sound field attributes and frequently employ sound field simulations to analyse the acoustic parameters of diverse church spaces and materials. Conversely, research on the soundscape in Islamic mosques prioritizes speech intelligibility and acoustic comfort, while studies of the soundscape of Buddhist temples gravitate towards the impact of natural and religious sounds on individuals. This paper anticipates the future direction of soundscape research on religious historical buildings.

Keywords Soundscape, Religious historical buildings, Sound environment, Visualized analysis

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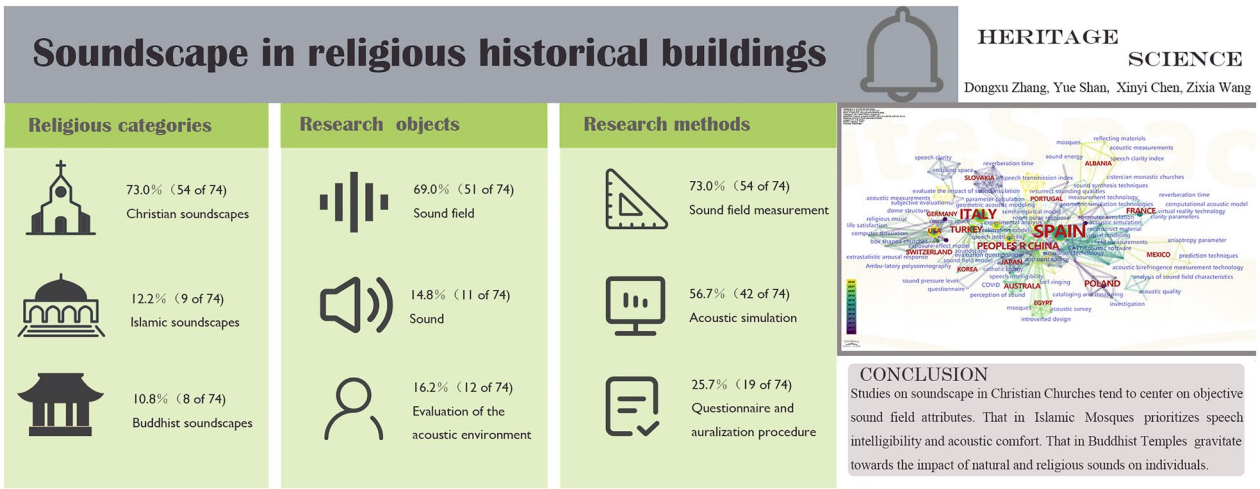
Graphical Abstract



Research aims

Religion, a socioideological construct with a deep-seated history, has been integral to human development by providing spiritual solace across epochs. The vast majority of extant religious historical buildings continue to serve as vital sites for disseminating religious culture and history and have concurrently become an important part of the world's architectural heritage. The soundscape of these historical religious buildings significantly influences the evocation of religious ambiance. Although this topic has received increased attention in recent decades in numerous interdisciplinary studies, review articles are relatively rare. Thus, the findings of previous publications need to be summarized. This paper seeks to address this gap by initially defining the concept of soundscape in religious historical buildings. Subsequently, it distils the research conducted over the past decade using quantitative statistics and a visual analysis from three perspectives: religious categories, research objects, and research methods. Potential research directions are predicted and analysed.

Introduction

The term "soundscape" was introduced by the Finnish geographer Granö in his 1929 work "Reine Geographie", where it was used to describe listener-centric acoustic environments [1]. In the 1960s and 1970s, the Canadian composer and environmentalist Schafer pioneered the study of soundscapes as an artistic concept and advocated for the creation of harmonious sound environments through listening and other means. Schafer's groundbreaking 1977 book, "The Soundscape: Our Sonic Environment and the Tuning of the World", served as a cornerstone for the field [2]. Schafer initiated "The World Soundscape Project" and defined a soundscape in the "Handbook for Acoustic Ecology" in 1978 as "the acoustic environment as perceived or experienced and/or understood by a person or people, in context." Soundscape research in Europe was further promoted through collections, books, and academic presentations.

In recent decades, soundscape research has experienced a worldwide surge. The International Organization for Standardization (ISO) issued a series of international standards related to soundscapes, namely, ISO 12913-(1–3) [3–5]. With contributions by scholars from diverse academic backgrounds, the scope of soundscape research has steadily broadened, yielding increasingly robust academic contributions. Review studies of soundscapes have covered the soundscapes of natural environments [6], psychoacoustic indicators in soundscapes [7], acoustic environments of heritage buildings [8], psychophysiological implications of soundscapes [9], social acoustic surveys of soundscape studies [10], and the impact of COVID-19 on soundscapes [11]. In 2016, Professor Kang, chair of the European Soundscape Alliance, edited "Soundscape and the Building Environment" [12] and provided a comprehensive overview of soundscape research from ten different perspectives. As the first book to systematically address soundscapes in the fields of architecture and the environment, it is a seminal work with considerable theoretical significance.

Soundscapes in religious historical buildings are increasingly recognized as vital components of intangible cultural heritage [13, 14]. To date, however, few studies have comprehensively summarized research on

soundscapes in religious historical buildings. Although some scholars have recently conducted a detailed analysis of the acoustics of occidental Christian churches [15], there is still a lack of collation and analysis of related research on soundscapes in the major world religions.

This paper reviews the research status of soundscapes in religious historical buildings over the past decade with regard to three aspects: religious categories, research objects and research methods. Religious categories are divided into Christianity, Islam, Buddhism and other religions; research objects include sounds inside and outside the building, the sound field and the evaluation of the acoustic environment; and research methods include measurements of the sound fields, acoustic simulations, questionnaires and auralization procedures.

Literature collection and statistics

In this paper, relevant terms pertaining to the soundscape in religious historical buildings were input into Web of Science (a globally recognized database reflecting the standard of scientific research) using the following search string: (religious buildings OR religion OR Christian OR church OR cathedral OR Islam OR mosque OR Buddhism OR temple OR worship) AND (soundscape OR sound environment OR sound field OR acoustics). The search method was a subject search. The search yielded a total of 472 papers, of which 338 were dated from January 2011 to December 2022. Subsequently, 264 papers were excluded based on relevance and other criteria. The inclusion criteria were as follows: (1) studies of religious buildings that did not focus on the soundscape (e.g., research on the images, history, culture, and belief of religious buildings); (2) soundscape studies at nontraditional religious sites (e.g., medical facilities); and (3) other unrelated research. After these exclusions, 74 journal articals were selected for analysis. Because the conference papers were not peer reviewed, they were not the core content of this study. However, considering the lack of journal papers in some research areas, 10 representative conference papers were selected as a supplement to this review.

From January 2011 to December 2022, research on soundscapes in religious historical buildings generally exhibited a progressively increasing trend, as depicted in Fig. 1a. Subjects related to the soundscape included the study of sound, the sound field and the human perception of sound. Currently, most related research focuses on the sound field. Figure 1b and c display statistics related to the first author of each paper and the publication journals. Figure 2 categorizes the papers according to their professional direction. The highest proportion, approximately 32%, comprises acoustical papers. Engineering papers follow at 13%, and architectural technology papers constitute approximately 12%. There are also papers from disciplines such as archaeology, religious studies, and art theory that demonstrate interdisciplinary interest in the soundscapes of historical religious buildings.

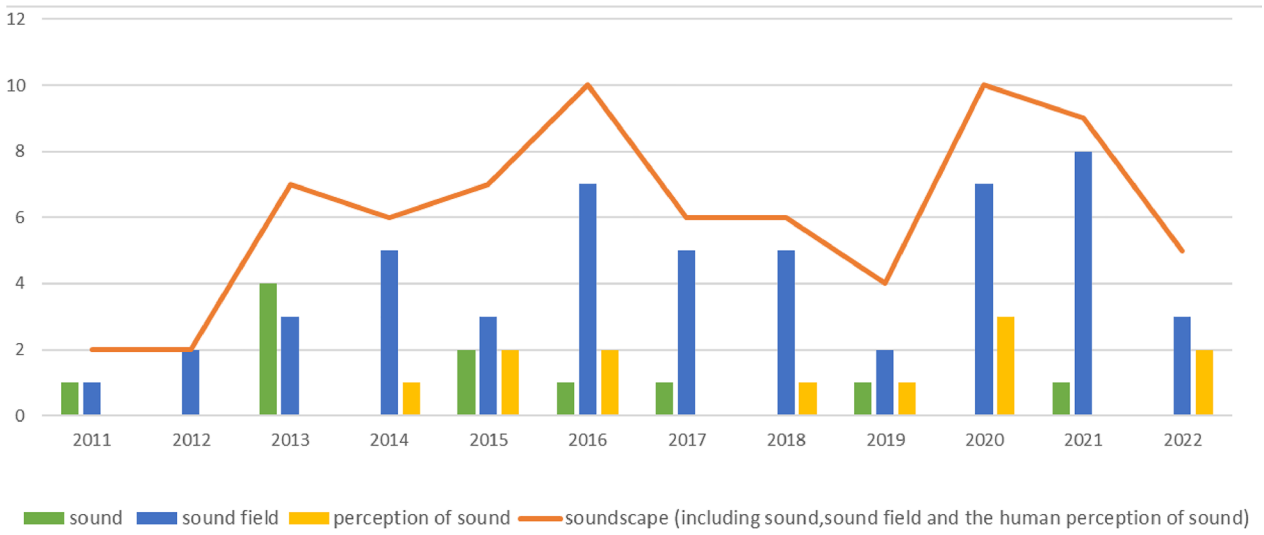
Citation statistics for the selected papers were compiled using Web of Science data. The average annual citations were chosen as the ranking criterion because earlier publication dates increase the likelihood of citation. Table 1 lists the top ten most cited papers. The paper with the highest annual citation rate was cited 7.8 times per year on average.

The visual analysis of keywords in these papers was performed with the author's country as the main cluster item. As depicted in Fig. 3a, the countries most actively engaged in researching soundscapes in religious historical buildings were Spain (22 papers) and Italy (9 papers), followed by China (7 papers), Poland (5 papers) and Turkey (4 papers). In addition, scholars from the U.S., France, Korea, and Japan made contributions to this area of study. Figure 3b presents a time map corresponding to the development of keywords in each cluster. The X-axis represents time nodes, while the Y-axis denotes clustered keywords. Scholars in Switzerland and Australia displayed a predilection for examining bells as their research object, while over the past five years, researchers in China and Turkey have considered the functional role of the soundscape in various spaces in religious buildings.

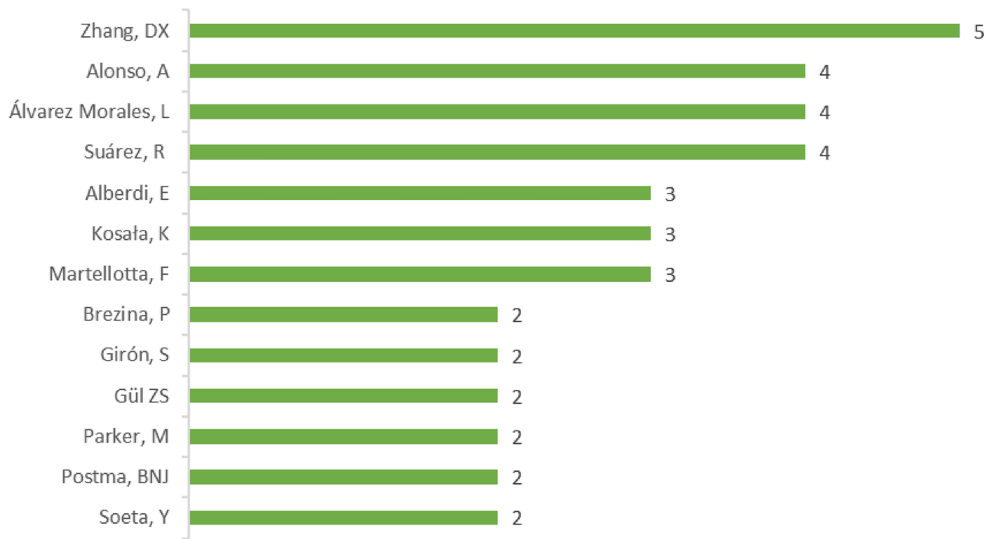
Before 2011, authors from Spanish, Italian, Portuguese, and Polish acoustic groups made numerous significant contributions to the study of religious soundscape. For example, Spanish and Italian authors devised semi-empirical models to elucidate the distribution of sound energy in distinct types of churches located in southern Spain and Italy [15]. Moreover, additional groundbreaking studies referenced in their research examined crucial facets of the sound environment within intricate Christian worship settings. These included the analysis of coupled spaces, subjective preferences, and the differential limitations of certain acoustic parameters within churches [15]. This work paved the way for further research.

Soundscape research in different religious categories

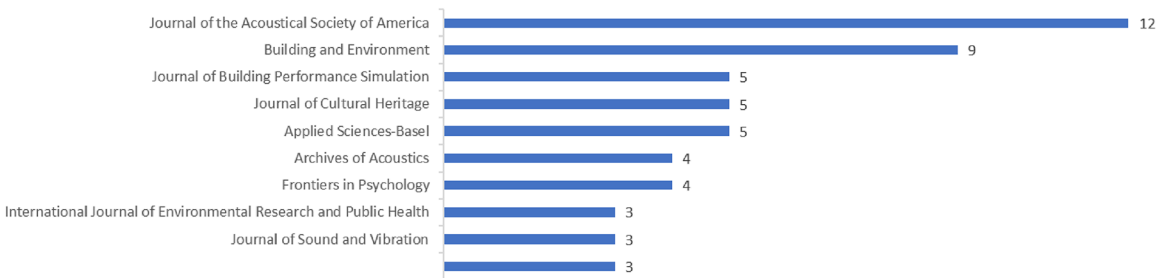
Christianity, Islam, and Buddhism are the three major religions worldwide and boast vast populations of adherents. Therefore, the most abundant research is on the soundscapes of the religious historical buildings of these three religions. Figure 4 shows the distribution of various religious soundscapes in the selected papers according to clustering analysis. The largest proportion of studies is devoted to the soundscape in Christian churches (73%), followed by Islamic mosques (12.2%) and Buddhist temples (10.8%). Research on the soundscapes of other



(a) Number of papers of religious soundscape in recent decade



(b) Number of publications by first authors



(c) Number of journals

Fig. 1 Religious soundscape research statistics

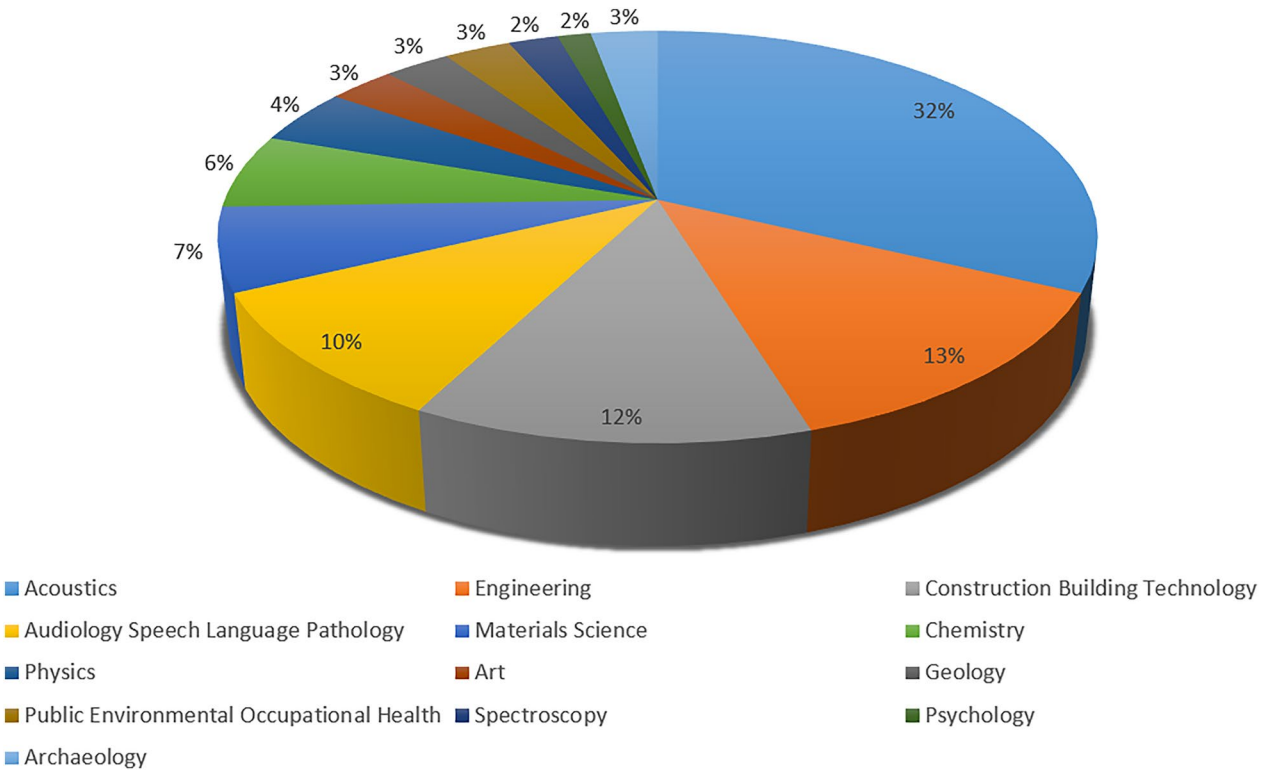


Fig. 2 The proportion of professional field research on soundscapes in religious historical buildings

religious buildings accounts for approximately 4% of studies.

Soundscapes in Christian churches

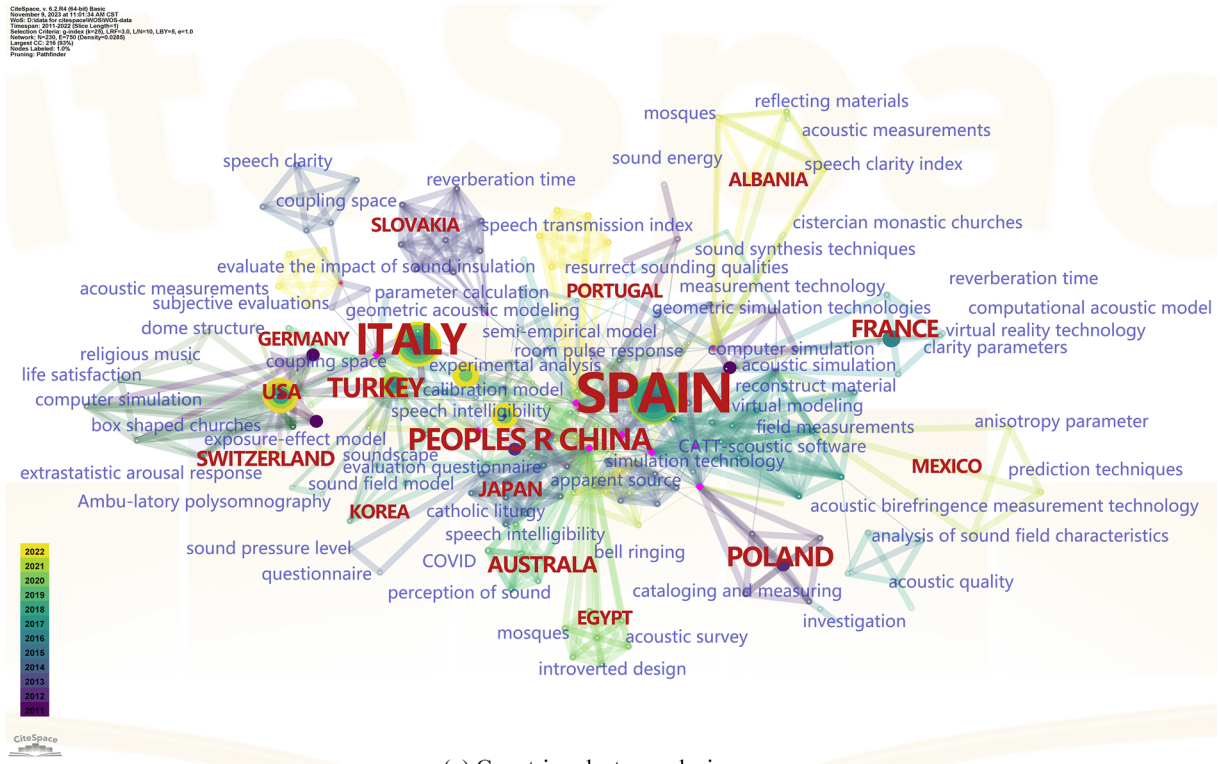
In the past decade, significant advances have been made in the study of soundscapes in traditional Christian churches in Europe. Numerous studies have investigated church bells and analysed their characteristics Research has investigated the relationship between the sounds of church bells and people's sleep at night using field investigation methods, and measures have been proposed to control noise [25, 26]. The history of the development of bells in the Roman Empire from the 1520 s to the end of the seventeenth century has been traced, and contemporary people's transformation and perception of the religious soundscape have been reconstructed [27]. Moreover, a methodology combining experimental and numerical techniques from materials science and music acoustics has been used to restore the bells from the church of S. Pedro de Coruche [28]. From an auditory health perspective, studies have been conducted to determine whether the sound of church bells causes hearing damage to bell ringers. The results show that church bell ringers do not present symptoms of occupational hearing loss, unlike musicians and construction workers [29].

In addition to research on bells, religious music constitutes a significant portion of the soundscape in traditional churches. Studies have examined two categories of vocal music in the Greek Orthodox Church: the Byzantine chant (BC) and ecclesiastical speech (ES). Through the analysis of acoustic parameters, it was demonstrated that BC and ES differ from each other as well as from common Greek speech and opera style [30]. Other studies have indicated that the most appropriate sound source positioning for music in churches is aligned with organ performance, an essential position in Baroque polychoral compositions [31].

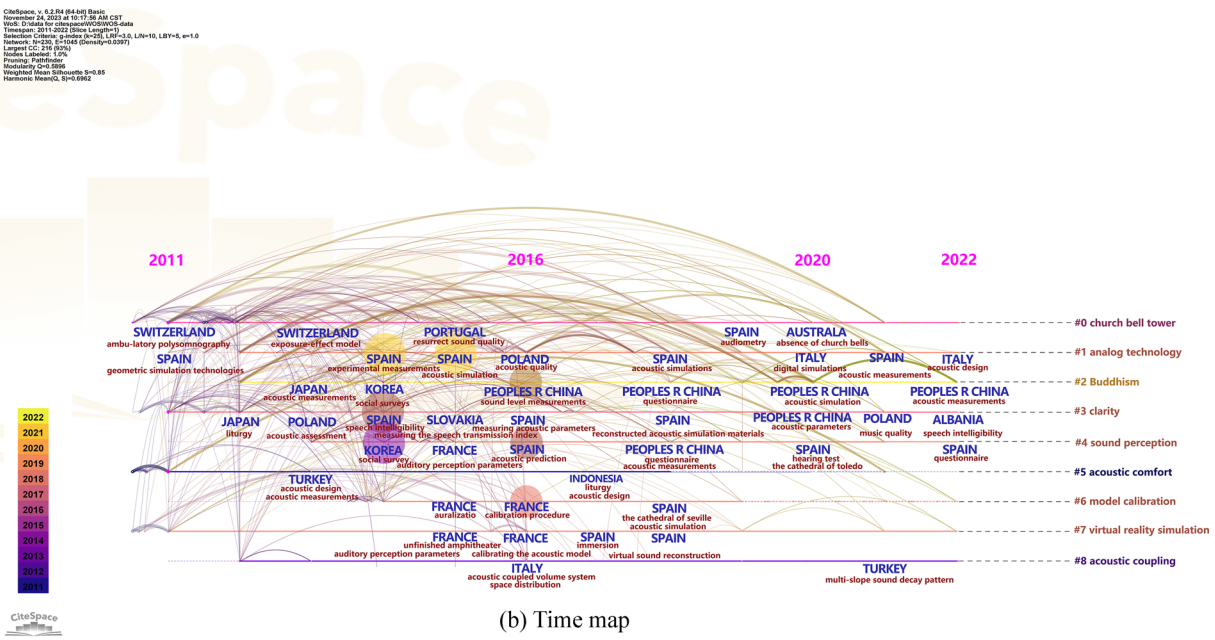
From the perspective of traditional acoustics, research has shown that in the surrounding environment of the church, vegetation plays a role in reducing noise in the church [32]. Various studies have concentrated on the influence of different architectural forms on the acoustic fields in churches, including Romanesque domed churches, Gothic basilicas [33] and Baroque domed churches [34]. Earlier churches with domes were designed as meeting and preaching spaces. They boasted suitable acoustics with midfrequency values of reverberation time (T_{30}) less than 1.0 s and speech transmission index (STI) values of 0.60. Following the proclamation of Christianity as an official religion, larger spaces were built to accommodate the growing numbers of faithful people.

Table 1 The top ten papers with the most annual citations

Authors/Years of publication	Titles of publications	Annual average number of citations/total citations	Keywords	Main contents
Postma et al. 2016 [16]	Perceptive and objective evaluation of calibrated room acoustic simulation auralizations	7.8/47	Ecological subjective listening test; perceptually valid auralizations	This paper examines the perceptual quality of room acoustic simulations and auralizations.
Girón et al. 2017 [15]	Church acoustics: A state-of-the-art review after several decades of research	6.8/34	Church acoustics; review; acoustic assessment	This paper describes and analyses the principal contributions to the acoustics of occidental Christian churches from the second half of the last century to 2017.
Suárez et al. 2016 [17]	Archaeoacoustics of intangible cultural heritage: The sound of the Maior Ecclesia of Cluny	5.8/35	Archaeoacoustics; worship acoustics; virtual acoustics	This paper strives to assess and recover the acoustics of a now extinct major religious space: the Maior Ecclesia in Cluny.
Zhang et al. 2016 [18]	Soundscape evaluation in Han Chinese Buddhist temples	5.8/35	Han Chinese Buddhist; temple; soundscape; evaluation	In this study, surveys conducted at four typical Han Chinese Buddhist temples are analysed to identify the subjective and objective factors that influence soundscape evaluations.
Álvarez-Morales et al. 2014 [19]	A methodology for the study of the acoustic environment of Catholic cathedrals: Application to the Cathedral of Malaga	5.1/41	Worship space acoustics; acoustics of cathedrals	This paper outlines the methodology used for the study of the acoustic environment of the Catholic cathedrals of southern Spain and applies it to the Cathedral of Malaga.
Berardi et al. 2014 [20]	Simulation of acoustical parameters in rectangular churches	4.5/36	Rectangular buildings; room acoustic simulation	This paper presents the results of computer simulations conducted on the acoustics of box-shaped churches.
Suárez et al. 2014 [21]	Sendra, Intangible cultural heritage: The sound of the Romanesque cathedral of Santiago de Compostela	4.4/31	Worship acoustics; Romanesque cathedral; religious music	This case study of the emblematic Cathedral of Santiago de Compostela employs computer simulation to expose the acoustic behaviour of the original Romanesque space, now covered by Baroque elements, and its effect on the functional and spatial structure.
Álvarez-Morales et al. 2015 [22]	A geometrical acoustic simulation of the effect of occupancy and source position in historical churches	4.2/30	Room acoustics; worship space acoustics	Acoustic simulations were undertaken using software based on calibrated models of six different churches.
Jeon et al. 2014 [23]	Soundscape evaluation in a Catholic cathedral and Buddhist temple precincts through social surveys and soundwalks	3.7/30	Soundscape evaluation; soundwalks	This study conducted social surveys and soundwalks in a Catholic cathedral and in Buddhist temple precincts in Seoul.
Alonso et al. 2014 [24]	Acoustic evaluation of the cathedral of Seville as a concert hall and proposals for improving the acoustic quality perceived by listeners	3.6/29	Cultural heritage; religious music	This acoustic evaluation of the cathedral of Seville as a concert hall was conducted by simulating acoustic models derived by modifying the model of the current state and calibrated using the results of in situ measurement.



(a) Countries cluster analysis



(b) Time map

Fig. 3 Visual analysis of religious soundscapes in the past decade

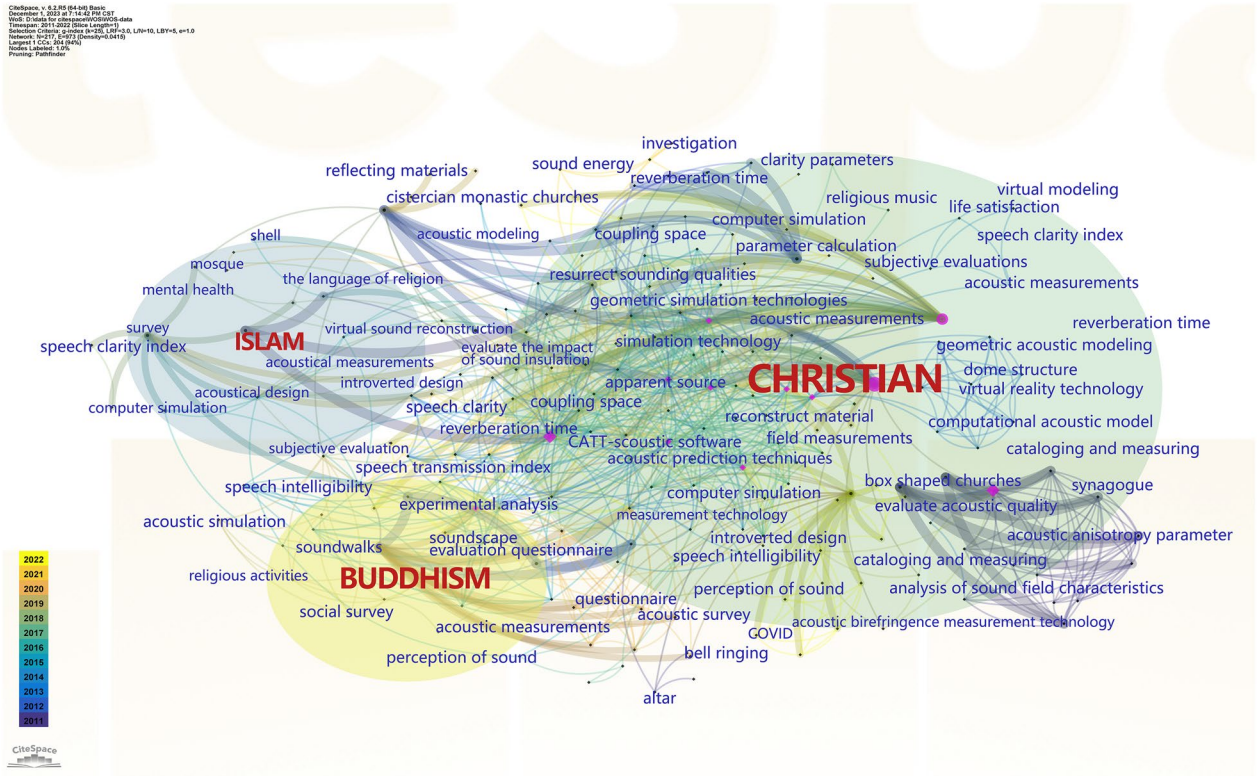


Fig. 4 Cluster analysis of religious categories

These spaces showed low acoustic absorption, with T_{30} mid values of 3.25 s in the basilicas and low STI values [34].

Scholars have examined the acoustics of Christian churches from varying perspectives. For instance, Jones's "Sound of Worship: A Handbook of Acoustics and Sound System Design for the Church" systematically expounds on the acoustic design of churches [35]. Similarly, Girón and others have described and analysed the principal contributions to the acoustics of occidental Christian churches from the second half of the last century to 2017 with a primary focus on ancient historical churches [15]. Important milestones in church acoustics include the Reformation and Counter-Reformation movements in the sixteenth century and the Second Vatican Council in the twentieth century [15]. In research on different subjects in Catholic churches after the Second Vatican Council, intelligibility has become a subject of primary importance, and many studies consider this aspect in their objectives [19, 36–38].

Because Christianity is one of the most influential religions globally, scholars worldwide have accorded great importance to the study of church soundscapes. While most related research has concentrated on the sound or sound field of traditional churches, investigations of people's feelings about the sound environment in these buildings have been relatively limited, indicating a potential area for further analysis.

Soundscapes in Islamic mosques

Over the past ten years, research on soundscapes in traditional Islamic architecture has been conducted primarily by scholars from Central and Western Asian countries. In Muslim society, the main activities in mosques are praying and listening to speech; therefore, the listener's understanding of speech is of paramount importance [39]. In terms of the acoustic parameters of traditional mosques, research has included the measurement and simulation of mosque sound fields. These studies have identified the types of mosques that are suitable for acoustic design, which has helped save materials, energy and time for future acoustic renovation or major building replacement [40]. Through the acoustic measurement of existing mosques and reconstruction of the architectural configuration of different spaces throughout history, the sounds of past mosques have been restored. This technique has become an important basis for archaeological acoustics [41]. Additionally, comparisons of acoustics and speech intelligibility between mosques as a function of the size, volume, occupancy and other parameters of

the main prayer hall have been used to develop a set of general acoustical guidelines for mosque design [42]. One study analysed the results of the room acoustic measurementsesults of a mosque to evaluate speech intelligibility and explain the sense of sacredness generated by sound within this sacred structure [43]. Further studies have analysed sound comfort and suggested a correlation between the acoustic design of mosques and the comfort level of the worshippers [44]. Some researchers have even argued that the main hall of the mosque may not be suitable for holding worship activities based on the consideration of acoustic comfort [45].

By underscoring the intimate relationship between traditional Muslim sonic performances and conventional Muslim architectural spaces, the book "Music, Sound, and Architecture in Islam" identifies Islam as an ideal site for investigating the relationship between sound and architecture, which in turn proves to be an innovative and significant angle from which to explore Muslim cultures [46]. This further highlights the role of acoustics in contributing to the overall spiritual experience in religious buildings and indicates a potential area for continued research and exploration.

Soundscapes in Buddhist temples

In the past ten years, scholars from East Asian countries, including China, Japan, and South Korea, have conducted research on soundscapes in historical Buddhist temples. Sound studies of Buddhist temples have shown that bells with a historical atmosphere positively impact people's subjective sound evaluations just as natural sounds do. Thus, the soundscape should align with the local natural environment and the historical and cultural background [47]. By recording the various sounds heard in Han Chinese Buddhist temples and analysing their acoustic parameters, research has shown that the physical acoustic and psychoacoustic parameters of these sounds correspond to the roles they play in the temple [48].

Comparative studies have also been conducted on the sounds of Buddhist temples and Catholic churches. These studies reveal that cathedral precincts play a more important role in social functions related to mainly visual components than temple precincts do, whereas functions for religious activities related to sound elements are emphasized more in temple precincts [23]. In terms of the sound field of Buddhist temples, scholars have discussed the acoustic characteristics of Japanese Buddhist temples in relation to sound source location and direction [49]. By combining sound field measurements with acoustic simulations, scholars have analysed the effects of spatial elements and sound source characteristics in the main hall of the Buddhist temple and found that both fabric sound absorbers and the position of Buddha statues had a pronounced effects on the sound field [50]. Additionally, the influence of the courtyard scale and layout factors on the sound field of Buddhist temple courtyards has been analysed [51]. In terms of soundscape evaluation, there is a significant correlation between the acoustic environment evaluation and the sound level measured in temples [18]. Among the physical acoustic and psychoacoustic parameters of the sounds in Han Buddhist temples, only sharpness is closely correlated with sound preference [48]. Researchers have also analysed the relationship between soundscape evaluations of Buddhist temples and mental health and have identified the influence of the degree of religious belief-related factors as a mediating variable [52]. However, research on soundscapes in Buddhist historical temples, especially traditional temples of Tibetan Buddhism and Theravada Buddhism, remains sparse, suggesting many potential areas for further study.

Although previous papers on soundscapes in religious historical buildings have mainly focused on the analysis of the three main world religions, some scholars have also explored soundscapes of other religions. For instance, a study explored the religious soundscape of Hindu traditions in Kerala and examined the role of sonic amplification in the sacrifices of Nambudiri Brahmins [53]. Using acoustic and perceptual measures, the voice characteristics of priests in Indian religion were investigated [54]. A study of the soundscape of Chinese Taoism, a tradition with nearly two thousand years of history, found that bird sounds significantly improved the acoustic comfort of Taoist priests [55]. These studies indicate that the soundscape in other religious buildings is an essential area for future research.

The above analysis has shown that the study of soundscapes varies significantly across different types of religions. Figure 5 presents a comprehensive overview of soundscape studies of religious historical buildings classified by discipline (the darker the colour, the richer the research findings). In the field of natural science, the most in-depth research has been conducted on soundscapes in Christianity. In the field of social science, there are relatively more studies on Islamic soundscapes. However, in the field of humanities, there are fewer studies on various types of religious soundscapes.

Soundscape research on different objects

Research on soundscapes in religious historical buildings has focused primarily on the following three objects: sound field, sound, and acoustic environment evaluation. The main research objects of various articles differ, as shown in the attached table. Sound field research, which accounts for approximately 69% of all papers, analyses

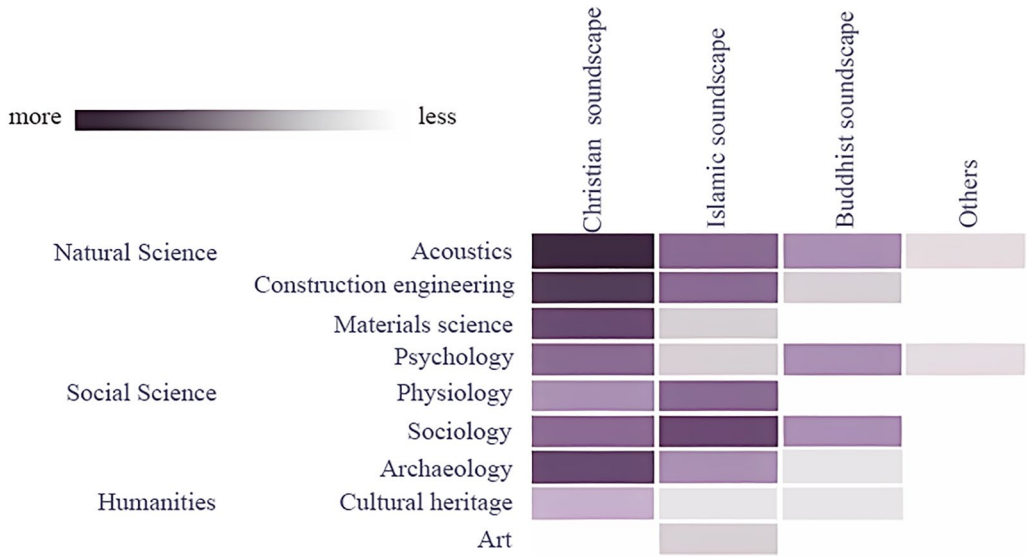


Fig. 5 Overview of religious soundscape research

the acoustic characteristics of the internal or external spaces of religious buildings. These characteristics include the reverberation time and the sound absorption or reflection coefficient of the inner surface materials of buildings. Sound research, which constitutes approximately 14.8% of studies, involves the analysis of sound parameters inside and outside buildings with certain religious characteristics. Both of these research fields focus on objective acoustic parameters. Soundscape evaluation, which accounts for approximately 16.2% of research, involves respondents' subjective feelings about the sound environment of religious historical buildings.

Sound field

To date, scholars have conducted measurement and simulation-related work on the sound field of religious historical buildings. These studies considered a variety of factors, such as building surfaces made of hard stone [22, 36], timber [43, 56], ceramic materials [57], and even soft materials [58–60]. Studies have also explored spaces of different sizes and shapes [31, 33, 61–71] and the impact of different positions of indoor furniture on the sound field [72]. Several studies have shown that the large places of worship in cathedrals are highly reverberant spaces [36, 73] with low speech intelligibility and that they are unsuitable for listening to spoken or musical sound signals [74]. The position of the sound source has no significant effect on the level of clarity [14]. In one case of Orthodox churches, although the reverberation time was longer than ideal for intelligibility purposes, the short source-receiver distance contributed to maintaining clarity within acceptable limits [75]. The results of a study of the Cathédrale Notre-Dame de Paris showed that compared to 2015 data, the reverberation time in worship spaces decreased significantly (20%) after the 2019 fire [76]. These works not only contribute to the understanding of the characteristics of the sound field but also improve the accuracy of sound field simulation. In addition, some researchers have used virtual acoustics to analyse the church space sound field [77.78]. For example, one study established virtual models to demonstrate that different structures and changes in furniture and paint had significant effects on the sound field of churches [72]. Another study used scaled-down physical models of a reverberant chamber to investigate how sound-absorbing materials such as curtains should be modelled in geometrical acoustic software when hung freely in ancient churches [58]. In a comprehensive investigation of room acoustics coupling, Hagia Sophia's rich formal and material characteristics were examined [79]. Other studies have shown that fabric sound absorbers and Buddha statues installed in the main hall have an obvious influences on the sound field of Buddhist temples [50]. An increase in the height of a temple courtyard wall increases sound reflection and, in turn, significantly increases the sound pressure level of each courtyard and making the sound fields more uniform [51].

Sound

The soundscape in religious historical buildings originates from sounds with religious characteristics, including bells, religious music, sounds of worship, and

chanting. These sounds, as part of historical and cultural heritage, are as ancient as the religious buildings themselves and serve to cleanse the minds of believers [48]. In the study of sounds in traditional religious places, some scholars have evaluated church sounds and the chants of monks to understand how religious sounds can be clearly and powerfully perceived [17]. Other studies have synthetically evaluated the acoustics of churches by defining a dual-composite index related to music and language [37].

From the perspective of archaeological restoration and historical preservation, many researchers have studied religious sounds as a special cultural heritage. For instance, the sounds of the Cistercian churches in Portugal are regarded as cultural heritage to safeguard the memory that is part of the cultural identity of the country [80]. Other researchers have reproduced the bells of Coruche (a damaged musical cultural relic) using archaeological means and have emphasized the importance of original sounds as cultural heritage [28]. With the support of new technology, scholars recovered one of the lost or forgotten intangible cultural heritage values of the cathedral of Santiago, the value of sound, which helped to establish its status as a factor in cultural dynamization [21].

It has been observed that the three main religions place different emphases on sound in religious historical buildings, which is likely due to varying religious doctrines and activities. Christianity worships God as the creator of heaven and earth without deliberately highlighting the status of humanity, so the focus of sound research is often bells and Christian music [27, 30, 31]. The main religious activities in Islam are reading and teaching the Quran, so the study of sound tends to focus on speech intelligibility in the religious venues [42, 43]. Buddhist doctrine emphasizes self-cultivation, with monks seeking their "true self" through daily chanting of the Buddhist scriptures. Most temples are located on scenic mountains, and research on sounds in Buddhist temples often focuses on natural sounds such as birds, wind, and rain or man-made sounds such as monks chanting, bells, and other ritual sounds [47, 48].

Evaluation of the acoustic environment

In the last decade, many studies on the subjective evaluation of soundscapes in religious historical buildings have focused on analysing the effects of acoustic comfort and sound on personal physical and mental health [18, 52]. For example, one study showed that the gurgling sound of water from a pond in front of a mosque could overcome background noise and put hearts at ease, thereby minimizing disruptions from screaming children or passing motorcycles [81]. The effect of activities in the sacred domains of the mosque on aural behaviours has also been tested [82]. An evaluation of the comfort of the acoustic environment in Chinese Buddhist temples indicated that when the sound level in a temple exceeded 60 dBA, respondents were more likely to feel uncomfortable. Furthermore, the correlation between the sound level and the evaluation of acoustic comfort increased significantly under these conditions [18].

In terms of the impact of sounds from religious buildings on human emotions or physical and mental health, one study aimed to investigate whether the emotions evoked by music were enhanced by the acoustics of the space in places of worship in Western countries. The outcome partially confirmed that some perceptual dimensions of music were perceived differently depending on the spatial acoustics [83]. Another study analysed the physiological influence of church bells on bell ringers. Although bells produced high-intensity sounds, the hearing loss to the ringer was very low. It is possible that bell ringers are only exposed to sound for only a short time at high sound pressure levels [29]. Other studies have demonstrated that religious sounds may have a significant effect on mental health and that Christian music may reduce anxiety [84]. Furthermore, the Quran's recitation may serve as an effective remedy for physical and mental ailments for followers of Islam [85], and there is variance in sound preferences among individuals in Buddhist temples with different mental health levels [52].

Soundscape research methods

The research methods used in the 74 papers on soundscapes in religious historical buildings were counted, and the results showed that sound field measurement methods were used in 54 papers, acoustic simulation methods in 42 papers, and questionnaire or auralization procedures methods in 19 papers (some of the papers adopted two or three types of research methods). Sound field measurements and computer acoustic simulations were primarily used to analyse objective acoustic parameters, while questionnaire and auralization procedure methods were utilized to analyse people's subjective perceptions of sound or sound environments in religious historical buildings.

Measurement of the sound field

Sound field measurements serve as a foundational method of acoustic research. This method measures acoustic parameters and different spatial elements, such as size, length, volume, style, material, and openness

in the sound field, to evaluate the spatial acoustic environment. Adherence to the international standard ISO 3382–1 (2006, 2009, 2010) is mandatory during the measurement process. With regard to Christian churches, one study chose 20 Orthodox churches that differed in terms of size, architectural style and other characteristics. The acoustic measurements showed that the clarity of music parameters (C_{80}) decreased as the volume of the room increased, except for one church made of wood [86]. Another study measured and analysed the acoustic properties of eight Roman Catholic churches in Poland and found that in addition to the increasing cubic capacity, the acoustic parameters worsened compared with the preferred values [38]. For the measurement of the sound field of mosques, a study selected and measured 20 mosques (nine semiclosed and 11 closed) and found a clear tendency towards increased reverberation in these buildings with an increase in the room's height and volume [87]. Concerning the measurement of the sound field in the main hall in Han Buddhist temples, a noticeable linear decline was found in the reverberation time, moving from low frequency to high frequency [50].

According to the sound field measurements of religious historical buildings, the reverberation time in Christian churches at 500 Hz predominantly ranges from 6–8 s, which is too long for preaching [19, 21, 22, 60, 88–90]. This time can exceed 10 s in larger cathedrals [24], far surpassing the reverberation times in Buddhist main halls [49, 50]. The likely explanation is that Christian believers associate taller building spires with proximity to God [33]. Many churches, as venues for daily religious activities, are constructed on a larger scale (exceeding 5000 cubic metres in volume). Additionally, church interiors typically feature stone materials with low sound absorption coefficients and are generally empty. In stark contrast, Buddhist temples are composed of multiple buildings scattered around a series of courtyards. Each individual building, including the main hall, is usually smaller than a church. Buddhist halls, which are made of wooden enclosures with poor airtightness, also employ methods to reduce reverberation time, such as hanging fabric sound absorbers indoors [50]. Consequently, the reverberation time in temples is significantly less than in churches (see Appendix).

Acoustic simulation

In recent decades, many scholars have adopted an approach that combines sound field measurements with acoustic simulations. This involves the use of computer simulation software such as EASE, CARA, CATT, ODEON, and RAYNOISE to construct virtual models of sound fields and analyse the acoustic impact of different building materials. The primary aim is to identify the characteristics and influencing factors of sound fields in both the indoor and outdoor spaces of religious historical buildings. The simulated spaces include various structural forms, such as towering churches [19, 24, 60, 70, 91, 92], domed mosques [40–42, 93], and traditional Chinese Buddhist temples [18, 50]. The most commonly used parameters in sound field simulation are reverberation time (RT) and early decay time (EDT), followed by the sound pressure level (SPL), sound clarity, and loudness.

In a representative study, scholars simulated 25 buildings by varying the size ratio of the length, width, and height. They considered the trade-off among the dimensional ratios of the room, volume and source position and presented formulas to predict acoustical parameters of box-shaped churches [20]. These authors concluded that the degree of crowding and type of surface material in religious places significantly affect the objective parameters of sound, particularly at low frequencies [94]. Other studies have demonstrated that the influence of clappers with different mechanical properties on church bells can be identified through parametric calculations [28]. Furthermore, researchers created a digital history reconstruction system through the application of acoustic technology simulation to restore the sounds of various religious ceremonies [88] and liturgies [95].

Questionnaire and auralization procedure

Questionnaire (and interviews) and auralization methods have been conducted with various categories of people to understand their subjective psychological and physiological responses to sound environments and to clarify the relationship between sound or the sound environment and individuals' feelings. These studies usually fall under the domains of psychology and sociology. As an important part of acoustic science, the study of psychoacoustics is currently receiving increasing attention [48].

The number of questionnaires has usually ranged from 30 to 600. For example, in a previous study, 521 questionnaires were distributed to believers and tourists in Buddhist temples. This study found that the overall evaluation of the acoustic environment in Buddhist temples and the preference for three sounds in Buddhist temples (i.e., bells, wind chimes and chanting sounds) were significantly correlated with the mental health of the respondents [52]. Another investigation was conducted in four typical Han Chinese Buddhist temples to identify the subjective and objective factors that influence soundscape evaluation [18]. Considering the recent

epidemic situation, the researchers compared bell-ringing practices in 2020 with a survey from 2018 in New South Wales, Australia, and concluded that bell-ringing practices in 2020 were heavily affected by regulations due to the COVID-19 pandemic, which impacted both the soundscape and those who valued sound [96, 97]. Furthermore, some studies have used in-depth interviews with individuals at religious sites and surrounding areas to explore the psychological and physiological reactions of believers and lay people and have proposed strategies for renovating the soundscape of churches [98], mosques [82], and Taoist temples [55].

Auralization procedures are performed through listening tests on auralized stimuli under laboratory conditions. The use of listening tests supported by virtual reality immersion in auralized religious historical buildings provides an appropriate scenario for quantifying acoustic experience and preferences within these sacred spaces. Postma and Katz presented a methodical calibration procedure for geometrical acoustic models using room acoustic prediction programmes based on geometrical acoustics to create realistic virtual audio realities or auralizations. A test case study was conducted for a typical seventeenth-century configuration of a former church [16]. In another study, listening tests were employed to investigate the subjective perception of the acoustic environment of seven cathedrals in the southern half of Spain. The analysis showed both independence of the recognition of reverberation and dependence on auralized signals based on instrumental music and female and male voices [89]. Another study used a subjective listening test to measure and simulate binaural auralizations and compared them according to eight acoustic perceptual attributes. A methodical calibration procedure was employed in combination with attention to control factors, which led to ecologically and perceptually valid auralizations. The test sites were three traditional churches [99].

Conclusions

Given that scholars worldwide are expanding their research on soundscapes in religious historical buildings, this study selected 74 relevant papers from the past ten years for systematic review and meta-analysis and sought to identify potential future research directions. These studies could be classified as soundscapes in Christian churches, Islamic mosques and Buddhist temples. Soundscape studies of Christian churches are the earliest and most numerous, while relatively little research has been conducted on the soundscapes of Islamic mosques, Buddhist temples or other religious buildings. Two main reasons are evident: on the one hand, modern acoustic research originated in the West; on the other hand, there is greater typological complexity in churches, and hence in their sound fields, than in mosques and Buddhist temples, which may present greater uniformity and a lower level of typological complexity. In terms of research objects and methods, many studies have focused on objective sound fields and sounds and have employed methods such as sound field measurements and computer simulations. Based on questionnaire surveys and auralization procedures, the influence of the soundscape in religious historical buildings on individuals' feelings has been determined.

In light of the above analysis, future research could compare soundscapes between different types of religious historical buildings or soundscapes in other religious historical buildings beyond the three major religions. Studies could also analyse the effect of religious architectural soundscapes on human physiological indices or adopt the methods from sociology, aesthetics and other disciplines for cross-disciplinary research. Despite the progress made, there is much to be done in this field. Collective effort from scholars worldwide is necessary to establish a cohesive research system, conduct a detailed analysis of the cultural and social value reflected in religious soundscapes, and identify the potential benefits to human health.

This review has certain limitations. It primarily selected architectural soundscape research on the world's three major religions and lacked an analysis of soundscapes of folk or local religions or of religious historical buildings centred on mythology (such as the Parthenon Temple). Only English-language literature was considered and the papers were manually selected, which may have led to some omissions. Nevertheless, by summarizing the current research status, readers can gain a broad understanding of recent decades of research on soundscapes in religious historical buildings. This paper also forecasts future research trends with the goal of promoting a more comprehensive understanding of soundscape studies.

Appendix

See Tables 2, 3, 4

Table 2 Research papers on soundscape in Christian historical buildings

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Brink et al., 2011 [25]	Sound/Switzerland	Church bell tower	Ambu-latory polysomnography(PSG); acoustic measurements	Church bell ringing events increase the probability of additional awakening reactions that would not take place if the ringing were suspended at night.
Segura et al., 2011 [90]	Sound field/Spain	Sant Jaume Basílica	Measurement technology (MLSSA and WinMLS) and two geometric simulation technologies (EPIDAURE and CATT)	The differences between the simulated values and the measured values for all parameters by both frequency and mean values, increase with distance.
Berardi, 2012 [37]	Sound field/Italy	The Cathedral of San Cataldo, the Church of Santa Maria della Consolazione, the Church of Santi Martina e Luca	Parameter calculation	This paper proposes a double synthetic index to evaluate the acoustics of a church. The index is obtained by combining the average values of seven parameters generally considered in studies of architectural acoustics.
Soeta et al., 2012 [66]	Sound field/Japan	4 Catholic churches	Acoustic measurements at different locations and directions	The speech transmission index was higher for the new Catholic liturgy, suggesting that the change in liturgy has improved speech intelligibility. Moreover, the interaural cross-correlation coefficient and early lateral energy fraction were higher and lower, respectively, suggesting that the change in liturgy has made the apparent source width smaller.
Delviniotis, 2013 [30]	Sound/Greek	Greek Orthodox Church	Sample analysis	The two vocal types of Byzantine music, sung and read, differ from each other and from common Greek speech and opera style with regard to the sound pressure level, the mean and standard deviation of frequency, the long-term average spectrum slope, and the relative level of the speaker.
Kosała et al., 2013 [38]	Sound field/Poland	Polish Roman Catholic churches	Investigation and analysis of sound field characteristics	Polish Roman Catholic churches of a small cubic capacity, especially historical wooden ones, are characterized by good acoustic parameters. Along with increasing cubic capacity, acoustic parameters worsen when compared to the preferred values.

Table 2 (continued)

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Omlin et al., 2013 [26]	Sound/Switzerland	Church bells in canton Zurich	Exposure-effect model; extrastatistic arousal response	The results suggest that up to 120–150 m from churches, more than one additional electroencephalography awakening on average occurs per night per person. A reduction in the number of awakening reactions of approximately 75% could be achieved by reducing the sound-pressure levels of bells by 5 dB.
Suárez et al., 2013 [33]	Sound field/Spain	The Church of Aquilea, early Christian basilica	Computer simulation and CATT-acoustic software	The early domus, with T_{30}, mid values under 1.0 s, with a full congregation and D_{50} and STI values of 0.60, were designed as places for meeting and preaching and generated private spaces for the faithful, who actively participated in the rites with suitable acoustics.
Alonso et al., 2014 [24]	Sound field/Spain	The Cathedral of Seville	Modelling; field measurements	The results led to the proposal of a new layout plan for an audience of 1500 people and other corrective measures in keeping with the history of the cathedral and compatible with its heritage value, improving subjectively perceived sound.
Álvarez-Morales et al., 2014 [19]	Sound field/Spain	The Cathedral of Malaga	Experimental measurements and simulation technology	When the source and receivers are in the choir, the results show that the choir is configured architecturally as a unique space within the Cathedral and can be considered a smaller volume with a more absorbent capacity due to the carved wooden seating.
Berardi, 2014 [20]	Sound field/USA	Misericordia (Rome); St. Michael's Church (Luneburg, Germany); Basilica of Santa Sabina all' Aventino (Rome); Padre Pio Pilgrimage Church (San Giovanni Rotondo, Italy) and Basilica of San Lorenzo (Florence)	Computer simulation method for calculating acoustic parameters of box-shaped churches	In rectangular churches, the acoustic conditions are particularly influenced by the typology of the church only when the volume is greater than 10,000 cubic metres. In churches of small volumes, the parameters show similar results for different typologies and internal organizations.

Table 2 (continued)

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Pedrero et al., 2014 [74]	Sound field/Spain	Toledo Cathedral	Data analysis	The cathedral cannot be understood as a single space since its various parts have different acoustic characteristics. These differences are not observed in traditional reverberation descriptors (T_{30}) but are noted in other room acoustic parameters.
Suárez et al., 2014 [21]	Sound field/Spain	The emblematic Cathedral of Santiago	Computer simulation methods	The lack of direct sound and nearby early reflections in many parts of the cathedral, in addition to the presence in many areas of source-receiver distances over 20–25 m, caused a major loss in speech intelligibility and musical clarity.
Álvarez-Morales et al., 2015 [22]	Sound field/Spain	The Abbey of Chiaravalle della Colomba; the church of San Fancesco; the Basilica of San Petronio; the Cathedral of Malaga; the church of Santi Martina and Luca	Modelling; acoustic simulation	The presence of the congregation led to substantial variations in T_{30} in historical churches, predominantly in the medium–high frequency range. This was particularly the case in churches where the occupied area was significantly larger than the total surface area.
Bradshaw et al., 2015 [84]	Perception of sound/USA	/	Statistics	The frequency of listening to religious music is linked to a reduction of death anxiety and increased life satisfaction, self-esteem and a sense of control.
Brezina, 2015 [14]	Sound field/Slovakia	The Christian Reformed Church in Kalinčiakovo; the St. Stephen-King Church; the Our Lady Queen of Angels Church	Measuring the speech transmission index (STI) and the rate of speech clarity (C_{50}) to evaluate speech intelligibility	The positions of the sound source (S) have no significant effect on the level of clarity. The research data are relevant for comparison with future similarly oriented research in smaller Romanesque churches (volume in the range of 300 to 600 m^3), which have previously been studied only minimally from an acoustic perspective.
Debut et al., 2015 [28]	Sound/Portugal	The bell from the church of S. Pedro de Coruche	Physics-based sound synthesis techniques	This paper examined the tuning properties of a damaged 13th-centurybell and resurrected its sounding qualities by combining experimental and numerical techniques from materials science and music acoustics.

Table 2 (continued)

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Elicio et al., 2015 [75]	Sound field/Italy	The Orthodox Church of San Nicola	Using microphone arrays to identify architectural elements versus acoustic effects	Although T_{30} was longer than ideal for intelligibility purposes, the short source-receiver distance contributed to maintaining clarity within acceptable limits.
Hahn, 2015 [27]	Sound/Germany	Bell-ringing in Lutheran Germany	/	In early modern Germany, there was no unified Lutheran soundscape; instead, a variety of locally or regionally confined soundscapes emerged, which were nonetheless each understood as distinctly Lutheran.
Postma et al., 2015 [99]	Perception of sound/France	Unfinished amphitheatre; the abbey Church Saint-Germain-des-Pres	Auralization; virtual reality technology; construction of geometrical acoustics models	The results of calibration show that the difference between the average sound absorption coefficient and the scattering coefficient of the simulation model and the measured value is within 1 JND (just noticeable difference). The calibrated simulation model can provide more accurate auditory perception parameters, such as early decay time (EDT) and clarity.
Alonso et al., 2016 [58]	Sound field/Spain	The tapestry hangs at Cologne Cathedral	Acoustic simulation; modelling	The effect of textiles on church acoustics proved to be more evident at medium frequencies than at low frequencies, as expected considering sound absorption coefficients. The reverberation times and centre time were affected most, while early-to-late energy ratios showed smaller variations, probably as a result of placing the material in a position that did not affect the stronger reflections.
Álvarez-Morales et al., 2016 [52]	Sound field/Spain	Andalusian cathedrals	Measuring acoustic parameters	The results confirm that both the distribution of the early reflected energy and the acoustic characteristics of reverberation, spaciousness, strength, and clarity support the favourable transmission of spoken or sung messages and music and exhibit remarkable dependence on sound-source location and its areas of influence.

Table 2 (continued)

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Iannace, 2016 [57]	Sound field/Italy	The Cathedral of Benevento	Measurement of the acoustic characteristics; study sound-absorbing materials; evaluate the impact of sound insulation systems on acoustic characteristics with room acoustics software	The introduction of material for acoustic correction reduced the length of the sound tail and improved both the understanding of speech and listening to musical performances.
Kosała, 2016 [70]	Sound field/Poland	Hungary Church	Using computational models to evaluate acoustic quality	The analysis showed that the audience improves the acoustic properties of the church, as indicated by a 23%higher average value of the global index GAP (Global Acoustic Properties) index = 0.8 and the distribution of GAP index values in the space defined by test points, which is more uniform compared with the church without an audience.
Martellotta, 2016 [63]	Sound field/Italy	Saint Peter's, St. John Lateran's; St. Paul's outside the Walls, and Saint Mary's Major	Measure and analyse the church as an acoustic coupled volume system	Coupling effects may play a major role in explaining how acoustic energy is distributed between subspaces depending on the source and receiver positions.
Postma et al.,2016 [16]	Perception of sound/France	Théâtre de l' Athénée; Notre-Dame Cathedral; and Saint-Germain—des—Prés Church	Calibration of geometric acoustic models; auralization; virtual reality technology	The results showed that the methodical calibration procedure employed in combination with attention to control factors led to ecologically and perceptually valid auralizations.
Suárez et al., 2016 [17]	Sound field/Spain	The Maior Ecclesia of Cluny	Acoustic prediction techniques based on computerized models; subjective perception to evaluate the sound quality of a space	High reverberation with mid-frequency values, T_{30}, mid, of 11 s, favoured acoustic conditions for the development of Gregorian melodic chant.
Alonso et al., 2017 [88]	Sound field/Spain	The Cathedral of Granada	Virtual modelling; acoustic simulation	Different music motifs: the various optimal conditions of reverberation associated with each musical motif exert a great influence on subjective perception. The high reverberation of the cathedral, close to 10 s, has a negative influence on any musical style.
Bäumer et al., 2017 [62]	Sound field/Germany	The city church of St. Michael in Jena	Collect subjective evaluations of sound before and after interior decoration; acoustic measurements	Objectively assessed the acoustics of the renovated rooms and the applicability of statistical computational models to develop possible improvements.

Table 2 (continued)

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Girón et al., 2017 [15]	Sound field/Spain	/	Church acoustics developed in each country	Findings and advances in each of these areas as well as perspectives on their future challenges were summarized and discussed in this work.
Kosała et al., 2017 [98]	Sound field/Poland	Orthodox Churches	Acoustic measurements	A single-number index for the assessment of acoustics in Orthodox churches was presented.
Małecki et al., 2017 [86]	Sound field/Poland	20 churches in Poland	Acoustic measurements; cataloguing and measuring rooms with different sizes, architectural styles; and other quality features	In larger churches, the T_{20} at 500 Hz was higher than the regression curve. This is probably a result of many small textile elements in small and medium churches, in contrast with large churches which are very austere in this respect.
Alonso et al., 2018 [56]	Sound field/Spain	The Cathedral of Seville	Acoustic measurements; model calibration and acoustic simulations	The objective assessment of the increase in sound absorption due to ephemeral decorations or mass occupation improves the acoustic behaviour of each of the different areas of the cathedral.
Martellotta et al., 2018 [59]	Sound field/Italy	St. John the Divine Cathedral	Acoustic measurements; geometric acoustic modelling	At low frequencies, measured values showed a significant influence of the supporting structure, The actual behaviour of the tapestries was estimated by subtracting the absorption of the flats up to 400 Hz (with some smoothing towards medium frequencies).
Martellotta et al., 2018 [64]	Sound field/Italy	The crypt of the Cathedral of Cadiz	Acoustic measurement; record and analyse room pulse response	In the rotunda, a non-diffuse sound propagation is formed in which, due to its shape, sound travels between the floor and the dome for a long time causing audible flutter echoes.
Sender et al., 2018 [67]	Sound field/Spain	Saint Jerome monastery	Reconstruct material and architectural features of hypothetical acoustic simulations	The position of the source has little effect on the overall average value for frequencies T_{30} and G. The worst results for intelligibility and clarity are found in the area under the choir.
Alberdi et al., 2019 [34]	Sound field/Spain	The church of San Luis de los Franceses	Acoustic measurements	For EDT values, the differences in early energy growth give rise to different behaviour as a function of the position of the source.

Table 2 (continued)

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
García et al., 2019 [29]	Sound field/Spain	The Cathedral of Valencia	Audiometry	The results show sound pressure levels reaching 120 dB inside the bell tower. The resulting hearing loss in bell ringers is small considering the great intensity of the sound produced by the bells.
Kim et al., 2019 [32]	Perception of sound/Korea	Myeong-dong Cathedral	Measurement; questionnaire	As the vegetation became established, the sound pressure level tended to be reduced more, with particularly significant decreases in the 1 kHz and higher bands.
Álvarez-Morales et al., 2020 [61]	Sound field/Spain	York Minster's Chapter House	Acoustic measurement and simulation techniques to analyse acoustic environments	The authors start by analysing the acoustic characteristics in relation to its original purpose as a meeting place for the cathedral's chapter and end by reflecting on its modern use for a variety of cultural events, such as concerts and exhibitions.
Carrillo et al., 2020 [56]	Sound field/Mexico	The Cathedral of Morelia	Acoustic birefringence measurement technology	Ultrasonic velocity data and scanning electron microscopy were performed to establish a direct correlation with the shear wave velocity and the acoustic anisotropy parameter developed on the naturally aged and unaged wood.
D'Orazio et al., 2020 [91]	Sound field/Italy	St. John's Baptistery	Measuring acoustic properties; calibration model	A comparison between hypotheses on early design of the architecture helped to highlight the influence of the ambulatory and the matroneum. The free path distribution, extracted by numerical simulation, confirmed that the behaviour of sound energy is concentrated in these areas and then released with some time-delay through the apertures between the columns.
Girón et al., 2020 [89]	Perception of sound/Spain	The Spanish Cathedrals; including the Cathedral of Cadiz; the Cathedral-Mosque of Cordoba; the Cathedral of Jaen; the Cathedral of Malaga; the Cathedral of Murcia; the Gothic Cathedral of Seville; and the Cathedral of Toledo	Acoustic measurement of binaural impulse response; audition test	Statistical analysis reveals that when listening pairs of cathedrals are used for comparison, the recognition of reverberation in cathedrals is independent of the existence of any respondent's background in acoustics in all spaces regardless of the type of musical or oral stimulus; furthermore, recognition is dependent on the listener's age.

Table 2 (continued)

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Katz et al., 2020 [76]	Sound field/France	The Cathédrale Notre—Dame de Paris	Acoustic measurements	Measurements were recently conducted on the construction site, 1 year since the fire. Compared to 2015 data, the reverberation time decreased significantly (20%).
Parker et al., 2020 [96]	Perception of sound/Australia	/	Survey and comparative method	The absence of church bells sounds made the COVID-19 silence even more pronounced.
Tronchin et al., 2020 [68]	Sound field/Italy	The S. Dominic Church of Foligno and Imola	Acoustic measurements; digital simulations	The challenge to adjust the acoustics of reverberant rooms such as churches to host musical venues has been achieved with a good quality of sound perception.
Alberdi et al., 2021 [31]	Sound field/Spain	The Church of Santa María Magdalena	Microphone recording; software simulation	Only the execution of the upper choir and organ sound source positions provides an equivalent sensation of musical and oral clarity and better subjective reverberation than the other combinations.
Alberdi et al., 2021 [72]	Sound field/Spain	The Church of San Luis de los Franceses	Field measurements and virtual models	The main objective was to analyse the evolution and perception of the sound field from the 18th to 21st centuries considering the different audience distributions and sound sources and modifications in furniture and coatings. There was a notable influence of the dome on the results for the different configurations studied.
Autio et al., 2021 [95]	Sound field/Sweden	The Vadstena Abbey Church	Digital reconstruction and acoustic analysis	The historical sound field in the church is characterized by the existence of two distinct acoustical subspaces within it. The subspaces show significantly better acoustic conditions for liturgical activities compared to the nave, which is very reverberant under the conditions of daily services.
Błaszczak et al., 2021 [69]	Sound field/Poland	St. James's Church; The Church of St. Hyacinth; The Church of the Virgin Mary	Acoustic measurements	Interesting similarities were found in the spatial distribution of individual acoustic parameters characterizing the distribution of the acoustic field in temples with completely different architecture.

Table 2 (continued)

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Parker et al., 2021 [97]	Sound field/Australia	Christian churches in the states of New South Wales and Victoria	Investigate church bells; the impact of COVID restrictions on the operations of church towers	While gradual return allowed the recommencement of activity, as the art form of bell ringing requires excellent timing, missing almost one year's worth of physical practice could negatively impact any art community.
Buratti et al., 2022 [92]	Sound field/Italy	The new auditorium of San Francesco al Prato in Perugia	Acoustic design and experimental analysis; room acoustic simulation	The acoustic quality indices gradually approached their optimal values for music listening during the works period. The average reverberation time changed from 4.56 s ante-operam to 1.96 s post-operam; C_{80} changed from a mean value of 4 dB to approximately 0.5 dB.
López-Mochales et al., 2022 [83]	Perception of sound/Spain	Christian Liturgical Spaces	Musical background questionnaire; statistical analysis	The acoustic signature of the four Christian temples causes an exaltation of certain emotions on listeners, although this effect is not associated with a particular musical piece.
Sukaj et al., 2022 [65]	Sound field/Albania	Byzantine Churches in Albania	Acoustic measurements	The results highlight slight difficulties in terms of speech understanding, especially given a speech clarity index found below the optimal range. This shortfall is attributed to the geometry of the volume and the reflecting materials applied to the surfaces that facilitate the build-up of sound energy.
Conference paper				
Postma et al., 2016 [73]	Sound field/France	The Cathédrale Notre-Dame de Paris	Room acoustic measurements and geometric acoustic models	Comparisons between results from two sessions show a significant decrease in reverberation time in the modern state. This change is attributed to the addition of carpet in several areas of the cathedral.
Postma et al., 2016 [77]	Sound field/France	The Cathédrale Notre-Dame de Paris	Virtual reality technology	A computational acoustic model was created and calibrated based on in situ measurements for reverberation and clarity parameters.

Table 2 (continued)

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Álvarez-Morales et al., 2017 [78]	Sound field/Spain	The Cathedral of Seville	Virtual reality technology	This paper shows the potential of virtual acoustic environments in research on church acoustics by providing the results of a preliminary experiment in the Royal Chapel of the Gothic Cathedral of Seville, southern Spain, designed to ascertain which factors clearly influence immersion.
Girón et al., 2017 [71]	Sound field/Spain	The Cathedrals of Murcia and Toledo	Acoustic measurements	The spatial distribution of several objective parameters is analysed in order to assess the acoustic quality of both musical and speech reproduction of the main temples.
Rodrigues et al., 2017 [80]	Sound/Portugal	Portuguese Cistercian Churches	Survey	In the Portuguese context, there is a diversity of Cistercian monastic churches. Its characterization allows acknowledgement of the interaction between the Cistercian liturgy and regionalism present in the country, resulting in a great diversity of soundscapes.

Table 3 Research papers on soundscape in Islamic historical buildings

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Sü Gül et al., 2013 [40]	Sound/Turkey	Dog˘ramacızade Ali Pasa Mosque	Acoustical design; acoustical measurements; computer simulation	The main prayer hall of Dog˘ramacızade Ali Pasa Mosque is a well-designed, modestly sized dome structure with appropriate absorptive and reflective interior finish materials and a strong outer shell, all creating a significantly more comfortable and acoustically superior interior environment.
Jafari et al., 2016 [85]	Perception of sound/Iran	/	Survey	The recitation of the Qur 'an and religious music has a positive impact on physical and mental health.
Kavraz, 2016 [94]	Sound field/Turkey	Mosque prayer hall	Simulate objective parameter values of sound	The results showed that the fullness of the prayer hall in the mosque and types of materials on surfaces could affect the objective parameter values of sound especially at low frequencies.
Suárez et al., 2018 [41]	Sound field/Spain	The Mosque of Cordoba	Virtual sound reconstruction	The increase in area and, consequently, in the volume of the temple, has generated significant deterioration of the acoustic conditions.
Ali et al., 2020 [82]	Perception of sound/Saudi Arabia	The Grand Mosque of Mecca	Survey and comparative method	The findings highlight the continued usefulness of domains for the contemporary study of research into the language of religion and for the study of broader semiotic assemblages present in the linguistic landscape.
Elkhateeb et al., 2021 [87]	Sound field/Egypt	Iwan-type masjids	Acoustic survey	All the masjids studied had an introverted design; thus, their contact with the external environment was restricted either to small, deep windows, or bent entrances.
Kitapci et al., 2021 [43]	Sound field/Turkey	The Aslanhane Mosque	Acoustic simulation; subjective evaluation	Although the Aslanhane mosque's subjective rating for speech intelligibility is "good," the overall low volume of the mosque and the lack of surface refections decrease the sensation of sacredness.
Sukaj et al., 2021 [93]	Sound/Albania	The Ottoman Mosques	Acoustic measurements	The acoustic characteristics of two mosques in Albania are analysed. These buildings have a squared plan layout surmounted by a dome at the centre of the space. The values of T_{30} are 2.0 s and 2.3 s, and both values of STI are 0.5.
Sü Gül, 2021 [79]	Sound field/Turkey	Hagia Sophia of Istanbul	Acoustic measurement; acoustic modelling; simulation and analysis	Among the many variables, the source-receiver distance and positioning within different subspaces appear to be the underlying determinant of multislope sound decay pattern.
Conference paper				

Table 3 (continued)

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Abdullah et al., 2013 [42]	Sound field/Malaysia	Masjid UPM\Masjid Jamek	Build a prediction model	The results of the analysis show that the overall acoustic and speech quality of Masjid Jamek is better when compared to the overall acoustic and speech quality of Masjid UPM. These results are then used to develop a set of design recommendations to ensure adequate speech intelligibility quality a mosque.
Othman et al., 2016 [44]	Sound/Malaysia	The Masjid Al-Hussain	Survey and comparative method	There is a correlation between the acoustic designs of the mosque and the worshipers' comfort.
Prawirasasra et al., 2017 [45]	Perception of sound/Indonesia	Syamsul Ulum Mosque	Analysis and measurement	The hall at Michigan State University is not acoustically comfortable enough to hold worship services.
Syamsiyah et al., 2018 [81]	Sound field/Indonesia	The Grand Mosque of Yogyakarta	Acoustic measurements	Background noise can be overcome with the gurgling sound of water in the pond in front of the mosque that can put hearts at ease so that noises from screaming children and passing motorcycles can be minimized.
Sukaj et al., 2021 [39]	Sound field/Albania	Ottoman mosques	Acoustic measurements	After comparing the acoustics of these two mosques, some solutions to improve the acoustics are suggested.

Table 4 Research papers on soundscape in Buddhist or other religious historical buildings

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Buddhism				
Ge et al., 2013 [47]	Sound/China	Jingci Temple	Collect soundscapes and subjective evaluations	Natural sounds, cultural sounds, and historic sounds were widely acclaimed in people's subjective feelings, which indicated the close relationships among the historical and cultural background, soundscape, and natural environment.
Soeta et al., 2013 [49]	Sound field/Japan	Japanese Buddhist temple	Acoustic measurements	The change in direction improves speech intelligibility, and the asymmetric property of direct sound and complex reflections from the altar and sidewall increases the apparent source width.
Jeon et al., 2014 [23]	Perception of sound/Korea	A Catholic Cathedral and in Buddhist temple precincts in Seoul	Social surveys and soundwalks	The cathedral precincts play a more important role in social functions related to mainly visual components than the temple precincts do, whereas the functions for religious activities related to sound elements are emphasized in the temple precincts.
Zhang et al., 2016 [18]	Perception of sound/China	Four typical Han Chinese Buddhist temples	Soundscape evaluation questionnaire; investigate subjective and objective factors influencing soundscape evaluations	There was little difference among the mean values of the day-long sound level measurements of the four temples and a significant correlation in the sound levels between each temple. The sound preferences are significantly correlated with sharpness value of the sounds in temples.
Zhang et al., 2018 [48]	Perception of sound/China	Han Buddhist temples	Questionnaire	The physical acoustic and psychoacoustic parameters of various sounds correspond to the roles they play in the temple. Buddhism-related man-made sounds dominate the sound environment in temples.
Zhang et al., 2020 [50]	Sound field/China	Main Hall of Chinese Buddhist temple	Sound field measurement and acoustic simulation	This study investigated the effects of spatial elements and sound source characteristics in a Main Hall and revealed that both fabric sound absorbers and Buddha statues had a pronounced effect on the sound field.
Zhang et al., 2020 [51]	Sound field/China	Han Buddhist temples	Sound field model; measurements	In traditional Buddhist temples, spatial elements, such as the height and sound absorption coefficient of temple courtyard walls, the position of courtyard partition walls, and the position and height of bell towers, could significantly affect the sound pressure level (SPL), reverberation time (RT), and musical clarity (C_{80}) of each courtyard.

Table 4 (continued)

Authors/years	Main research objects/countries	Buildings	Methods	Key findings
Zhang et al., 2022 [52]	Sound field/China	Han Buddhist temples	Questionnaire	The results indicated that for the respondents, the overall acoustic environment of Buddhist temples was significantly correlated with mental health and that a preference for three sounds in Buddhist temples, i.e., bells, wind chimes and chanting sounds, was significantly correlated with mental health.
Taoism				
Xie et al., 2022 [55]	Soundscape evaluation/China	Laojundong Temple in Chongqing	Questionnaires and interviews	With the increasing proportion of the natural elements in the visual landscape in the temple, the acoustic comfort of Taoist priests and lay people increased significantly with the addition of bird sounds. However, with the increasing proportion of Taoist scenes, Taoist music only significantly improved the acoustic comfort and heart rate of lay people.
Hinduism				
Balasubramanium et al., 2019 [54]	Sound/India	Indian Hindu	Acoustic simulation; the Praat software and the Speech tool; survey	The results did not reveal any vocal deviations in purohits using perceptual and traditional acoustic measures. In contrast, the Indian Hindu purohits had higher intensities and increased cepstral values compared with normal controls.
Gerety 2017 [53]	Sound/India	In the sacrifices of Nambudiri Brahmins	Microphones and loudspeakers	In contrast to the private sacrifices of previous generations, "amplified sacrifice" is now carried out as a public Hindu festival with thousands of attendees and a full suite of marketing and media coverage. In this way, the local, sonic amplification of performance tracks with a regional, cultural "amplification" of Vedic ritual and Nambudiri identity.

Abbreviations

ISO	The International Organization for Standardization
COVID-19	Coronavirus Disease 2019
BC	Byzantine Chant
ES	Ecclesiastical Speech
T_{30}	Reverberation Time
STI	Speech Transmission Index
C_{50} (C_{80})	Clarity Index
RT	Reverberation Time
EDT	Early Decay Time
SPL	Sound Pressure Level
PSG	Polysomnography
JND	Just Noticeable Difference
GAP	Global Acoustic Properties Index
SPL	Sound Pressure Level

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Author contributions
DZ: writing–original draft. YS: writing, investigation, data curation. XC: collection, charting. ZW: data collection.

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Availability of data and materials
Data availability is not applicable to this article as no new data were created or analysed in this study.

Declarations

Competing interests
The authors declare that they have no competing of interests.

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